NOAA Technical Memorandum NESDIS NGDC-26

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UNITED STATES DEPARTMENT OF COMMERCE

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1. Introduction

In October 2008, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed an integrated bathymetric–topographic digital elevation model (DEM) of Nantucket, Massachusetts (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). The 1/3 arc-second[1] coastal DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by PMEL to simulate tsunami generation, propagation and inundation. The DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 3) and designed to represent modern morphology. It will be used for tsunami forecasting as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a description of the data sources and methodology used in developing the Nantucket DEM.

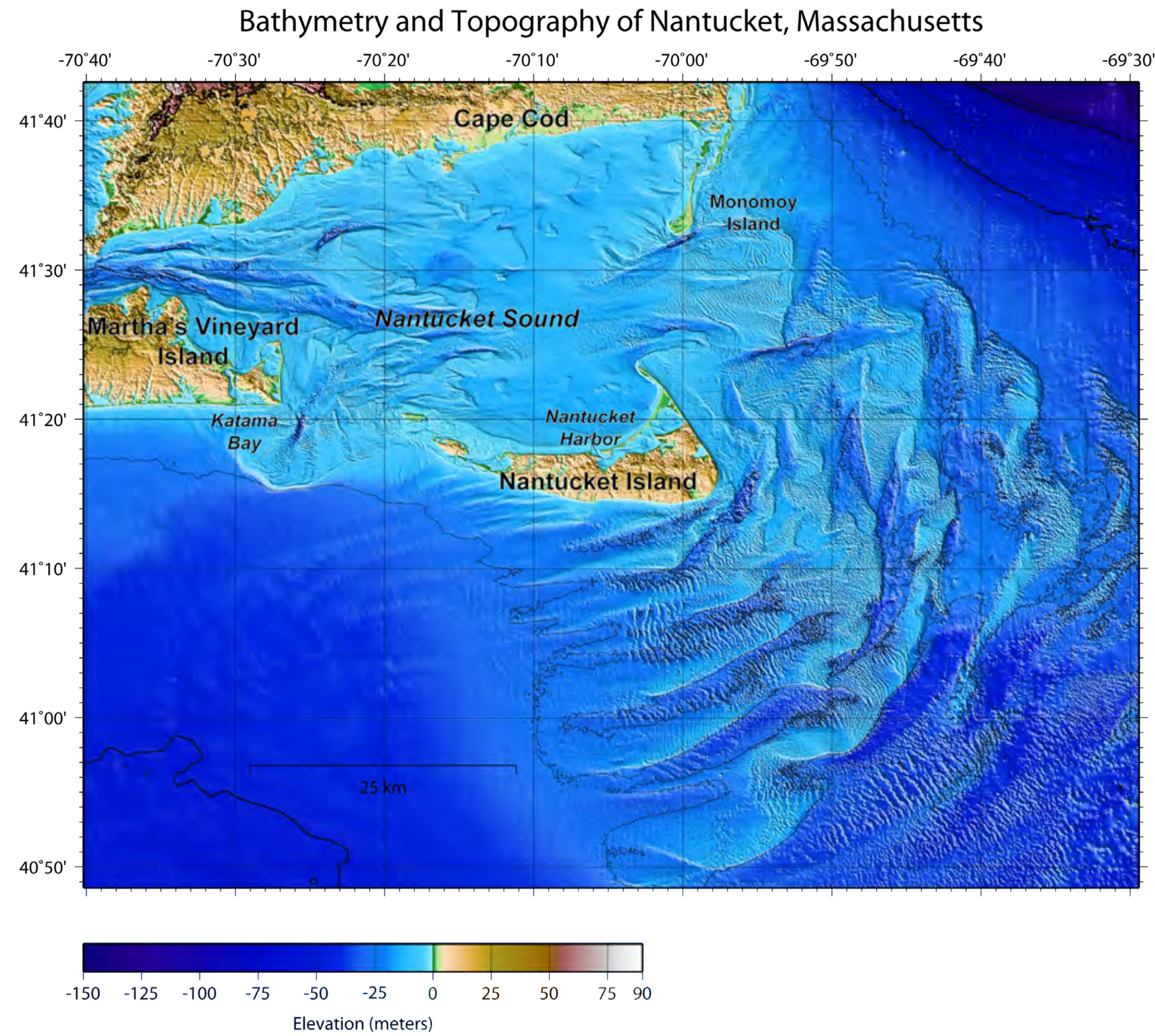

Figure 1. *Shaded-relief image of the Nantucket DEM. Contour interval is 25 meters.*

1. The Nantucket DEM is built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Nantucket, Massachusetts (41°17′ N, 70°6′ W) 1/3 arc-second of latitude is equivalent to 10.283 meters; 1/3 arc-second of longitude equals 7.757 meters.

2. Study Area

The Nantucket DEM covers the coastal region surrounding the town of Nantucket, Massachusetts on Nantucket Island (Fig. 1). It spans Nantucket Sound, from Martha's Vineyard on the west to Nantucket Island on the east, and north to Cape Cod, and extends into the Atlantic Ocean.

The coastal morphology of the Cape Cod and Nantucket Sound region can vary rapidly as alongshore currents move sediment along the coast. For example, in April 2007, a breach was opened along the southern shore of Katama Bay on Martha's Vineyard (Fig. 2; *Sigelman, 2007*), dramatically altering current dynamics and sediment erosion, migration and deposition in the area.

Figure 2. *April 19, 2007 photograph of the breach in Norton Point Beach. Norton Point Beach is a barrier sand bar along the southern edge of Katama Bay that connects the islands of Martha's Vineyard and Chappaquiddick, though it occasionally opens up, as it did on April 17, 2007, disconnecting the two islands. [Photo credit: Trustees of Reservations (TTOR), http://www.mvtimes.com/news/2007/04/19/norton_point_beach.php]*

3. Methodology

The Nantucket DEM was constructed to meet PMEL specifications (Table 1), based on input requirements for the development of reference inundation models (RIMs) and standby inundation models (SIMs) (*V. Titov, pers. comm.*) in support of NOAA's Tsunami Warning Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North America Datum of 1983 (NAD 83) and mean high water (MHW), for modeling of maximum flooding, respectively.[2] Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1: PMEL specifications for the Nantucket DEM.

Grid Area	Nantucket, Massachusetts
Coverage Area	70.67º to 69.49º W; 40.81º to 41.71º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	MHW
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI Arc ASCII grid

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEM. Most GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant for our purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the wave's passage across ocean basins. This DEM is identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic. At the scale of the DEM, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 3) were obtained from U.S. federal and state agencies including: NOAA's Office of Coast Survey (OCS), Coastal Services Center (CSC), and NGDC; the U.S. Geological Survey (USGS); the U.S. Army Corps of Engineers (USACE); and the Massachusetts Office of Geographic and Environmental Information (MassGIS). Satellite imagery, taken by Digital Globe and extracted from *Google Earth Pro*, was used for estimating bathymetry in areas with recent, significant morphologic change. Safe Software's *FME* data translation tool package was used to shift datasets to NAD 83 geographic horizontal datum and to convert them into ESRI *ArcGIS* shapefiles[3]. The shapefiles were then displayed with *ArcGIS* to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using *FME*, based on data from NOAA tide stations in the region. Applied Imagery's *Quick Terrain Modeler* software was used to evaluate processing and gridding techniques.

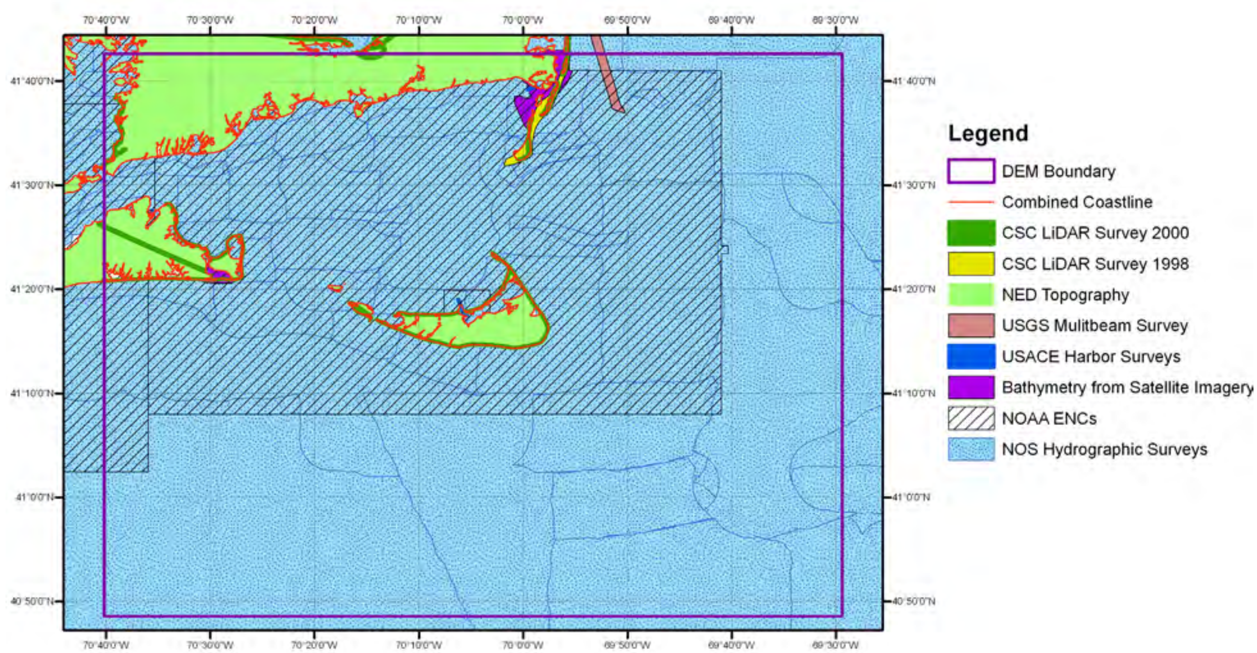

Figure 3. *Source and coverage of datasets used in compiling the Nantucket DEM.*

3. *FME* uses the North American Datum Conversion Utility (NADCON; http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.html) developed by NOAA's National Geodetic Survey (NGS) to convert data from NAD 27 to NAD 83. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformations.

3.1.1 Shoreline

Coastline datasets of the Nantucket region (Table 2) were obtained from OCS and MassGIS, and were used to develop a "combined coastline" for the Nantucket DEM.

Table 2: Shoreline datasets used in developing the Nantucket DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NOAA OCS	2007	Nautical charts	1:10,000 to 1:80,000	WGS 84 geographic	MHW	http://nauticalcharts.noaa.gov/mcd/enc/
MassGIS	1992	Digitized 1:24,000 USGS DLG	1:25,000	NAD 83 Mass State Plane (meters)		http://www.mass.gov/mgis/cs.htm

1) NOAA Nautical Charts

Sixteen NOAA Nautical Charts were available for the Nantucket area (Table 3), and were downloaded from the OCS web site (http://nauticalcharts.noaa.gov/mcd/enc/). All charts are available as georeferenced Raster Navigational Charts (RNCs; digital images of the charts), which were used to assess the quality of bathymetric datasets. Six charts were also available as NOAA Electronic Navigational Charts (ENCs)[4] that represent chart features as individual digital objects. The ENCs are in S-57 format and include coastline data files referenced to MHW. Coastlines from several of the larger scale RNCs, along with identified jetties, were manually digitized by NGDC and included in the combined coastline for Nantucket. The ENC digital coastlines contained many piers and other manmade structures that had to be removed when building the combined coastline.

Table 3: Nautical charts available in the Nantucket region.

Chart #	*Chart name*	*Scale*	*Format*	*ENC #*
13200	Georges Bank and Nantucket Shoals	1:400,000	RNC,ENC	US3EC09M
13204	Georges Bank, Eastern Part	1:220,000	RNC	
13218	Martha's Vineyard to Block Sound	1:80,000	RNC, ENC	US4MA23M
13228	Westport River and Approaches	1:20,000	RNC	
13229	South Coast of Cape Cod	1:40,000	RNC	
13230	Buzzards Bay	1:40,000	RNC, ENC	US5MA25M
13232	New Bedford Harbor and Approaches	1:20,000	RNC	
13233	Martha's Vineyard	1:40,000, w/1:20,000 inset	RNC	
13235	Woods Hole	1:5000	RNC	
13236	Cape Cod Canal and Approaches	1:20,000	RNC, ENC	US5MA27M
13237	Nantucket Sound and Approaches	1:80,000	RNC, ENC	US4MA43M
13238	Martha's Vineyard Eastern Part	1:20,000, w/ 1:10,000 insets	RNC	
13241	Nantucket Island	1:40,000	RNC	
13242	Nantucket Harbor	1:10,000	RNC, ENC	US5MA40M
13244	Eastern Entrance to Nantucket Sound	1:40,000	RNC	
13248	Chatham Harbor	1:20,000	RNC	

4. The Office of Coast Survey (OCS) produces NOAA Electronic Navigational Charts (NOAA ENC®) to support the marine transportation infrastructure and coastal management. NOAA ENC®s are in the International Hydrographic Office (IHO) S-57 international exchange format, comply with the IHO ENC Product Specification and are provided with incremental updates, which supply Notice to Mariners corrections and other critical changes. NOAA ENC®s are available for free download on the OCS web site. [Extracted from NOAA OCS web site: http://nauticalcharts.noaa.gov/mcd/enc/]

2) Massachusetts Office of Geographic and Environmental Information coastline

MassGIS modified the USGS 1:24,000 hydrography digital line graph (DLG) quadrangle files to produce the Massachusetts coastline. MassGIS reformatted the DLG files into Arc/INFO coverages and projected them into the Massachusetts State Plane Coordinate system, NAD 27. The coastline was then extracted from the files and edited. Polygon topology was also created for each quadrangle. The coverages were then projected into the Massachusetts State Plane Coordinate system, NAD 83 (meters). This coastline contains many manmade features, such as piers, that had to be removed from the dataset by NGDC (e.g., Fig. 4).

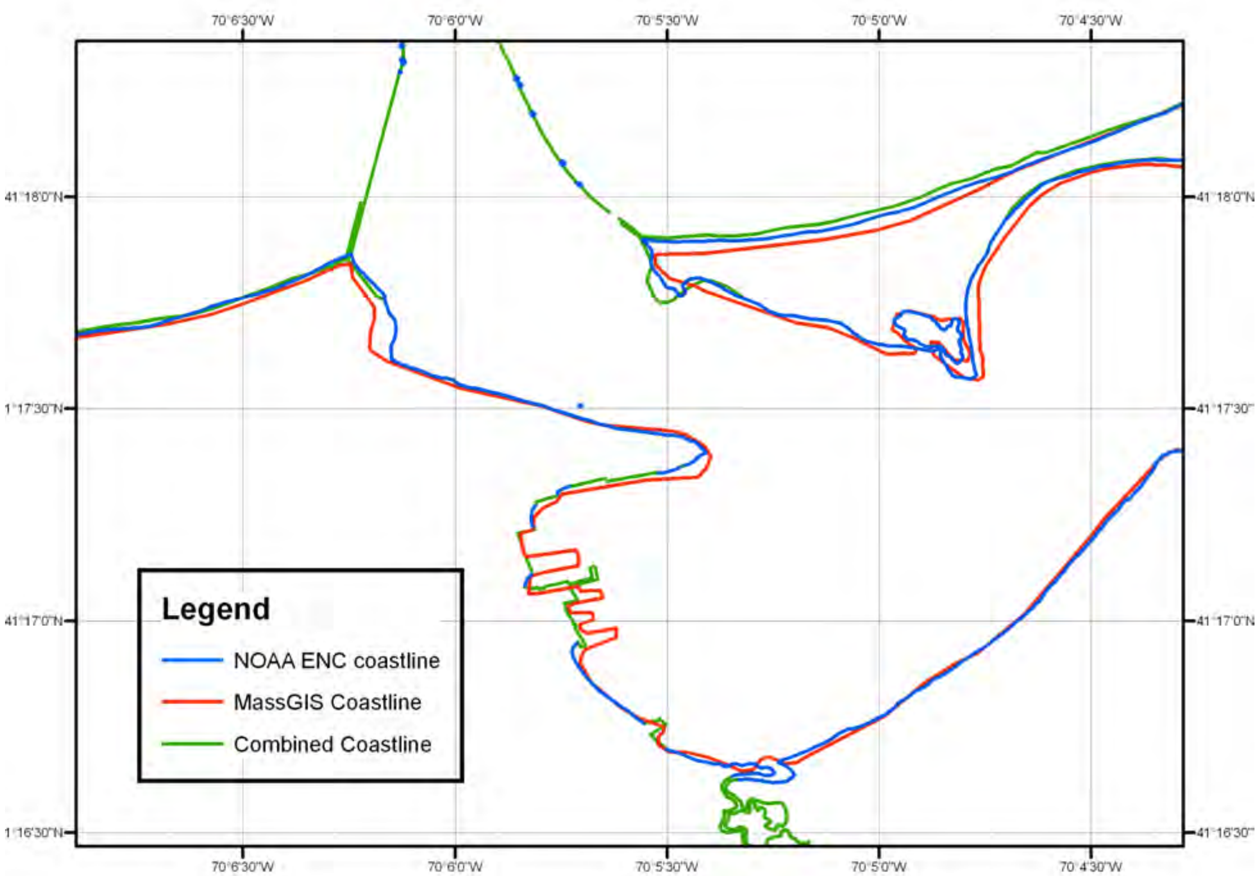

Figure 4. *Digital coastline datasets at the mouth of Nantucket Harbor. The combined coastline built by NGDC was adjusted to fit high-resolution coastal lidar data. It also captures the east and west jetties, which are not represented in the NOAA ENC and MassGIS coastlines. NOAA ENC and MassGIS coastlines also contained piers and other manmade coastal structures that had to be removed in developing the combined coastline.*

The ENC and MassGIS coastlines were integrated into a combined coastline for the Nantucket region, which was then adjusted to align with the large-scale RNCs, high-resolution coastal lidar data, and satellite imagery in three areas (e.g., Fig. 5) where recent, significant morphologic change has occurred. The west and east jetties at the mouth of Nantucket Harbor are submerged at high tide, with the exception of the ends nearest the beach. The east jetty has a cut part way out, visible in satellite imagery, that is scoured to a depth of 18 feet (*Nantucket Harbor Master, pers. comm.*). These features were manually digitized by NGDC for representation in the combined coastline and the Nantucket DEM (Fig. 4). The combined coastline was converted to xyz data with 10 meter point spacing, using NGDC's *GEODAS* software, to build a pre-surfaced bathymetric grid (see Sec. 3.3.3).

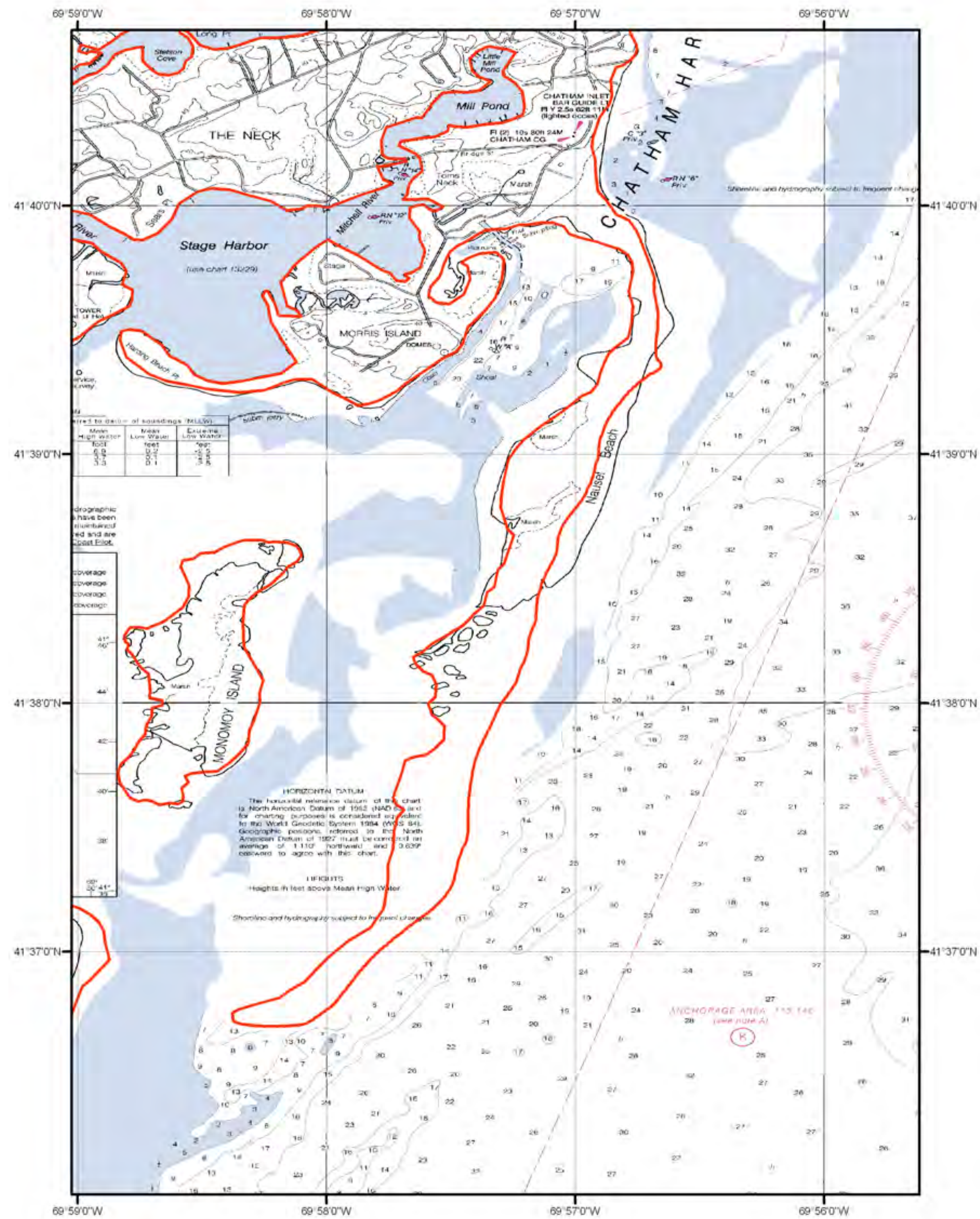

__Figure 5.__ Recent morphologic change at south end of Cape Cod. Nauset Beach has grown rapidly southward, as observed in a 2008 satellite image and a 2000 coastal lidar survey and represented in the NGDC combined coastline (bold red line). RNC #13248 in background.

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the Nantucket DEM included NOS hydrographic surveys, USGS multibeam swath sonar surveys, extracted NOAA ENC sounding data, USACE hydrographic harbor surveys, and Digital Globe satellite imagery in three areas with recent, significant morphologic change (Table 4; Fig. 3). NGDC also digitized soundings at the mouth of Nantucket Harbor. Datasets were originally referenced to MHW, mean low water (MLW) or mean lower low water (MLLW).

Table 4: Bathymetric datasets used in compiling the Nantucket DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1889 to 2004	NOS hydrographic survey soundings	Ranges from 10 meters to 1 kilometer (varies with scale of survey, depth, traffic, and probability of obstructions)	NAD 27 or NAD 83 geographic	MLW or MLLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
USGS	1998 to 2004	Multibeam swath sonar	4 meters	NAD 83 geographic	MLLW (meters)	
NOAA ENC	2006 to 2007	Extracted soundings	1:10,000 to 1:80,000	WGS 84 geographic	MLLW (meters)	http://nauticalcharts.noaa.gov/mcd/enc/
USACE	2004 to 2007	Hydrographic surveys	Scattered soundings and channel profiles	NAD 27 or NAD 83 Mass State Plane (feet)	MLLW (feet)	http://www.nae.usace.army.mil/navigation/navigation2.asp?mystate=ma
Digital Globe	2008	Satellite imagery	Several meters	Undefined	Undefined	
NGDC	2008	Digitized depths	Meters to 10s of meters	WGS 84 geographic	MHW (meters)	

1) National Ocean Service hydrographic survey data

A total of 86 NOS hydrographic surveys conducted between 1889 and 2004 were available in digital form for use in developing the Nantucket DEM (Table 5; Fig. 6). The hydrographic survey data were originally vertically referenced to MLW or MLLW and horizontally referenced to either NAD 27 or NAD 83 geographic datums. Three of the older surveys (H01948, H05141 and H05249) were not used in building the Nantucket DEM as they have been superseded by more recent surveys, with the exception of the inset for H01948, which had to be manually digitized by NGDC.

Data point spacing for the NOS surveys varied by collection date. In general, earlier surveys had greater point spacing than more recent surveys. All surveys were extracted from NGDC's NOS Hydrographic Survey Database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) referenced to NAD 83. The surveys were subsequently clipped to a polygon 0.05 degrees (~5%) larger than the Nantucket DEM area to support data interpolation along grid edges.

After converting all NOS survey data to MHW using *FME* (see Sec. 3.2.1), the data were displayed in ESRI *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets and edited as necessary. The surveys were also compared to the topographic and bathymetric datasets, the combined coastline, and NOAA RNCs. The surveys were clipped to remove soundings that overlap more recent NOS, USGS and USACE bathymetric surveys.

Table 5: Digital NOS hydrographic surveys in the Nantucket region.

Survey ID	*Year*	*Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
H01948	1889	20,000	MLW	Digitized in NAD 27
H05141	1931	20,000	MLW	NAD 27
H05227	1932	40,000	MLW	NAD 27
H05249	1932	40,000	MLW	NAD 27
H05275	1932	100,000	MLW	NAD 27
H05276	1932	100,000	MLW	NAD 27
H05543	1934	20,000	MLW	NAD 27
H05588	1934	20,000	MLW	NAD 27
H05589	1934	10,000	MLW	NAD 27
H06348	1938	5,000	MLW	NAD 27
H06349	1938/42	10,000	MLW	NAD 27
H06350	1938/42	20,000	MLW	NAD 27
H06439	1939	60,000	MLW	NAD 27
H06441	1939	120,000	MLW	NAD 27
H06446	1939	40,000	MLW	NAD 27
H06447	1939	80,000	MLW	NAD 27
H06468	1942	10,000	MLW	NAD 27
H06469	1939/42	10,000	MLW	NAD 27
H06470	1939	10,000	MLW	NAD 27
H06471	1939	10,000	MLW	NAD 27
H06472	1939	10,000	MLW	NAD 27
H06473	1939	10,000	MLW	NAD 27
H06531	1939	10,000	MLW	NAD 27
H06532	1939	20,000	MLW	NAD 27
H06533	1939/42	10,000	MLW	NAD 27
H06534	1939	20,000	MLW	NAD 27
H06558	1940	40,000	MLW	NAD 27
H06559	1940	40,000	MLW	NAD 27
H06561	1940	10,000	MLW	NAD 27
H06562	1940	10,000	MLW	NAD 27
H06563	1940	40,000	MLW	NAD 27
H06712	1940	20,000	MLW	NAD 27
H06713	1940	20,000	MLW	NAD 27
H06714	1940	20,000	MLW	NAD 27
H06742	1942	20,000	MLW	NAD 27
H08111	1953	10,000	MLW	NAD 27
H08170	1954	5,000	MLW	NAD 27
H08171	1956/60	20,000	MLW	NAD 27
H08172	1954/56	20,000	MLW	NAD 27
H08348	1955/56	10,000	MLW	NAD 27
H08349	1956	10,000	MLW	NAD 27
H08350	1956	40,000	MLW	NAD 27
H08409	1957	25,000	MLW	NAD 27
H08449	1958	10,000	MLW	NAD 27
H08450	1958	20,000	MLW	NAD 27
H08484	1959	10,000	MLW	NAD 27
H08497	1958/59	10,000	MLW	NAD 27

Survey ID	*Year*	*Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
H08599	1961	40,000	MLW	NAD 27
H08600	1961	40,000	MLW	NAD 27
H08601	1961	40,000	MLW	NAD 27
H08602	1961	20,000	MLW	NAD 27
H08603	1960/61	20,000	MLW	NAD 27
H08631	1960/61	10,000	MLW	NAD 27
H08760	1963	10,000	MLW	NAD 27
H08761	1960/64	12,500	MLW	NAD 27
H08820	1964	10,000	MLW	NAD 27
H08821	1964	10,000	MLW	NAD 27
H08824	1963	12,500	MLLW	NAD 27
H08845	1964	10,000	MLW	NAD 27
H08846	1964/65	12,500	MLW	NAD 27
H08847	1965	20,000	MLW	NAD 27
H08902	1966	10,000	MLW	NAD 27
H08903	1966	10,000	MLW	NAD 27
H08905	1966	20,000	MLW	NAD 27
H09233	1971	20,000	MLW	NAD 27
H09615	1976	20,000	MLW	NAD 27
H09661	1976/78	10,000	MLW	NAD 27
H09668	1976/77	10,000	MLW	NAD 27
H09712	1977	10,000	MLW	NAD 27
H09724	1977	10,000	MLW	NAD 27
H09750	1978	10,000	MLW	NAD 27
H10186	1985	40,000	MLLW	NAD 27
H10191	1985	40,000	MLLW	NAD 27
H10192	1985	40,000	MLLW	NAD 27
H10198	1985	10,000	MLLW	NAD 27
H10498	1993/94	10,000	MLLW	NAD 83
H10504	1993/94	10,000	MLLW	NAD 83
H10511	1993	10,000	MLLW	NAD 83
H10520	1994	10,000	MLLW	NAD 83
H10547	1994	10,000	MLLW	NAD 83
H10556	1994	10,000	MLLW	NAD 83
H10563	1994	10,000	MLLW	NAD 83
H10817	1998	10,000	MLLW	NAD 83
H11077	2001	5,000	MLLW	NAD 83
H11078	2001	10,000	MLLW	NAD 83
H11079	2004	20,000	MLLW	NAD 83
H11318	2004	10,000	MLLW	NAD 83

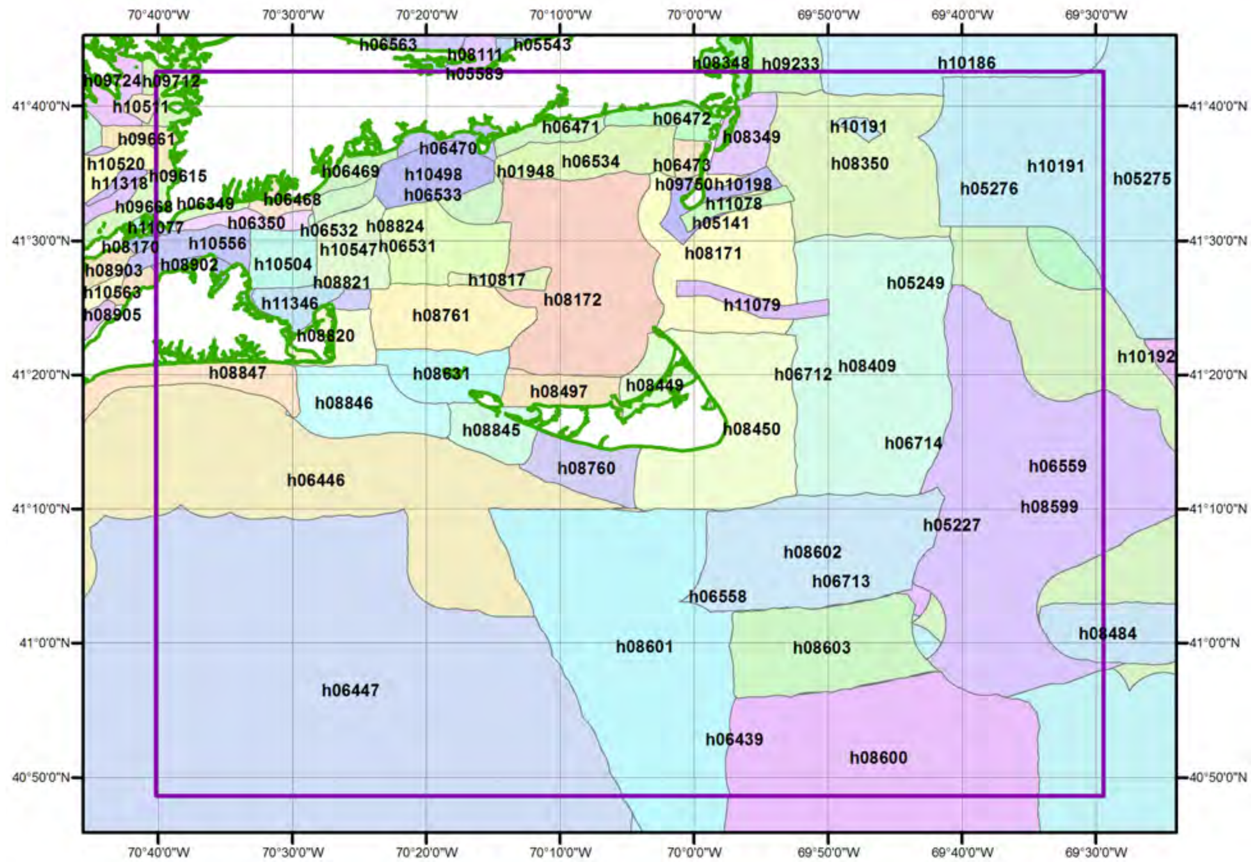

Figure 6. *Digital NOS hydrographic survey coverage in the Nantucket region. Some older surveys were not used as they have been superseded by more recent surveys. DEM boundary in purple; combined coastline in green.*

2) U.S. Geological Survey multibeam swath sonar surveys

Two multibeam swath sonar surveys conducted in Massachusetts waters (Table 6) were available from USGS: one along the eastern seaboard of Cape Cod, conducted on the Canadian Coast Guard vessel *Frederick G. Creed*, and another at the eastern entrance to Nantucket Sound, conducted aboard the NOAA ship *Thomas Jefferson* in cooperation with NOS. Bathymetric data from the 1998 Cape Cod[5] survey (Fig. 7) were compiled into 4-meter grids in NAD 83 geographic coordinates and MLLW vertical datum (*Poppe et al., 2006*). Bathymetric data from NOS survey, H11079, conducted in 2004, were compiled into 3-meter grids in NAD 83 geographic and MLLW vertical datum (*Poppe et al., 2007*). NGDC downloaded the bathymetric grids from the USGS web site and evaluated them with *ArcGIS*; NOS survey H11079 (Table 5; Fig. 6) was also available as point data through NGDC's NOS Hydrographic Survey Database.

Table 6: USGS multibeam swath sonar surveys used in compiling the Nantucket DEM.

Survey ID	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Resolution*
90815	1998	MLLW	NAD 83 geographic	4m grid
H11079	2004	MLLW	NAD 83 geographic	3m grid

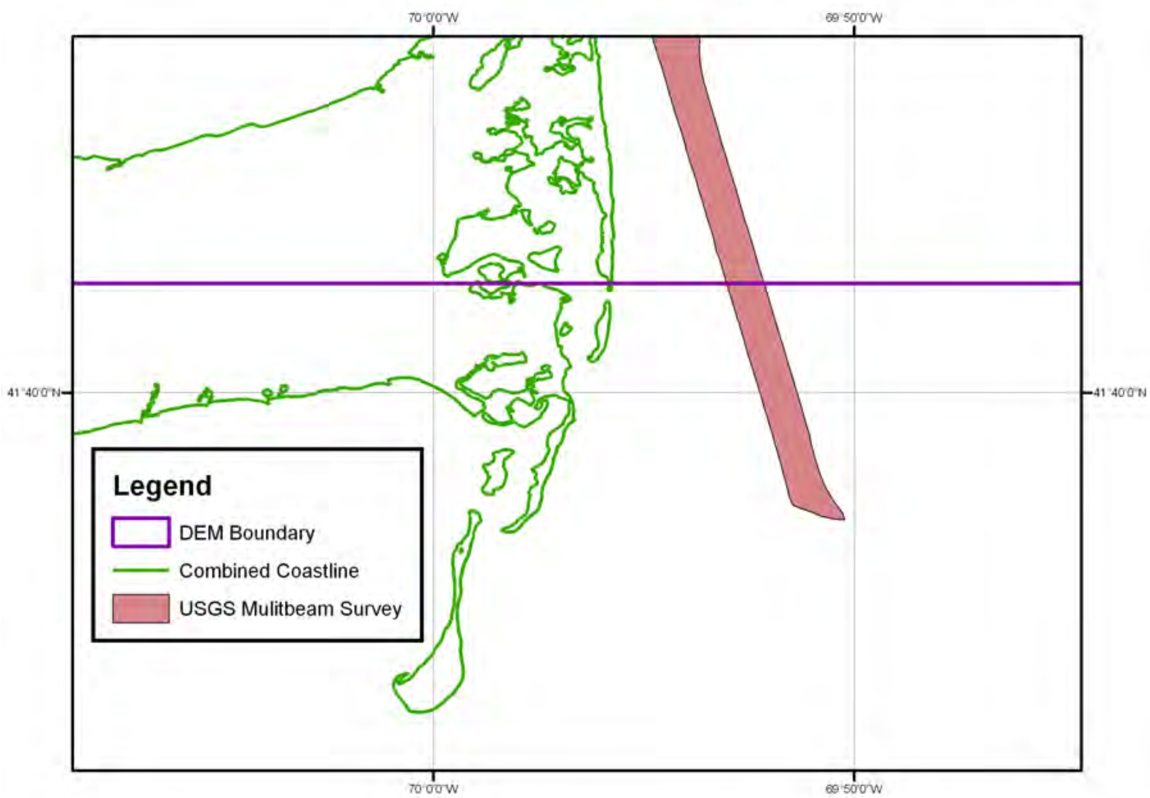

Figure 7. *Coverage of southern half of USGS multibeam swath sonar survey east of Cape Cod. DEM boundary in purple; combined coastline in green.*

5. This data set includes bathymetry of the sea floor offshore of eastern Cape Cod, Massachusetts. The data were collected with a multibeam sea floor mapping system during USGS survey 98015, conducted November 9 - 25, 1998. The surveys were conducted using a Simrad EM 1000 multibeam echosounder mounted aboard the Canadian Coast Guard vessel Frederick G. Creed. This multibeam system utilizes 60 electronically aimed receive beams spaced at intervals of 2.5 degrees that insonify a strip of sea floor up to 7.5 times the water depth (swath width of 100 to 200 m within the survey area). The horizontal resolution of the beam on the sea floor is approximately 10% of the water depth. Vertical resolution is approximately 1 percent of the water depth. [Extracted from metadata]

3) NOAA Electronic Navigational Chart soundings

NOAA ENC sounding data were extracted from charts #13218, 13230, 13236, 13237, and 13242. Chart #13242 covers Nantucket Harbor, while chart 13237 spans Nantucket Sound. Elevations of wrecks and exposed rocks were also extracted from these two ENCs. Soundings and submerged wreck depths are in WGS 84 geographic and MLLW datums, while exposed rocks and wrecks are referenced to MHW.

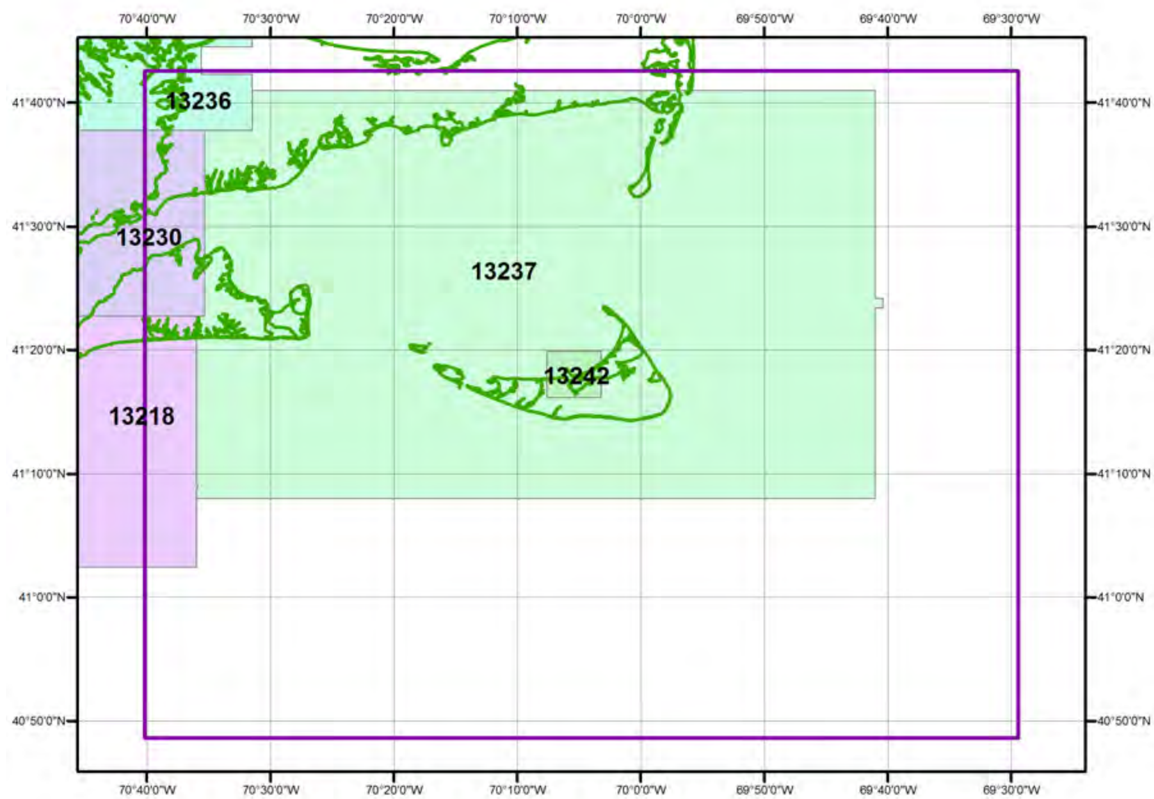

Figure 8. Coverage of NOAA ENCs in the Nantucket region. DEM boundary in purple; combined coastline in green.

4) U.S. Army Corps of Engineers hydrographic surveys of harbor channels

USACE conducted three surveys at the harbor entrances in the Nantucket region: Nantucket Harbor, Chatham (Stage) Harbor[6] and Vineyard Haven Harbor[7] (Table 7; Fig. 9). All data were originally in Massachusetts State Plane coordinates (Island or Mainland) and either NAD 27 or NAD 83 horizontal datums. Depths were in feet relative to MLLW.

Table 7: USACE hydrographic sonar surveys used in compiling the Nantucket DEM.

Location	*Year*	*Original Vertical Datum (feet)*	*Original Horizontal Datum (feet)*	*Spatial Resolution*
Nantucket Harbor	2004	MLLW	NAD 27 Mass State Plane Island	Profiles 60 to 300 meters long, spaced 30 meters apart, with 6-meter point spacing
Vineyard Haven Harbor	2004	MLLW	NAD 27 Mass State Plane Island	Scattered soundings, 6 to 20 meters apart
Chatham (Stage) Harbor	2007	MLLW	NAD 83 Mass State Plane Mainland	Profiles 75 to 100 meters long, spaced 10 to 20 meters apart, with 3-meter point spacing

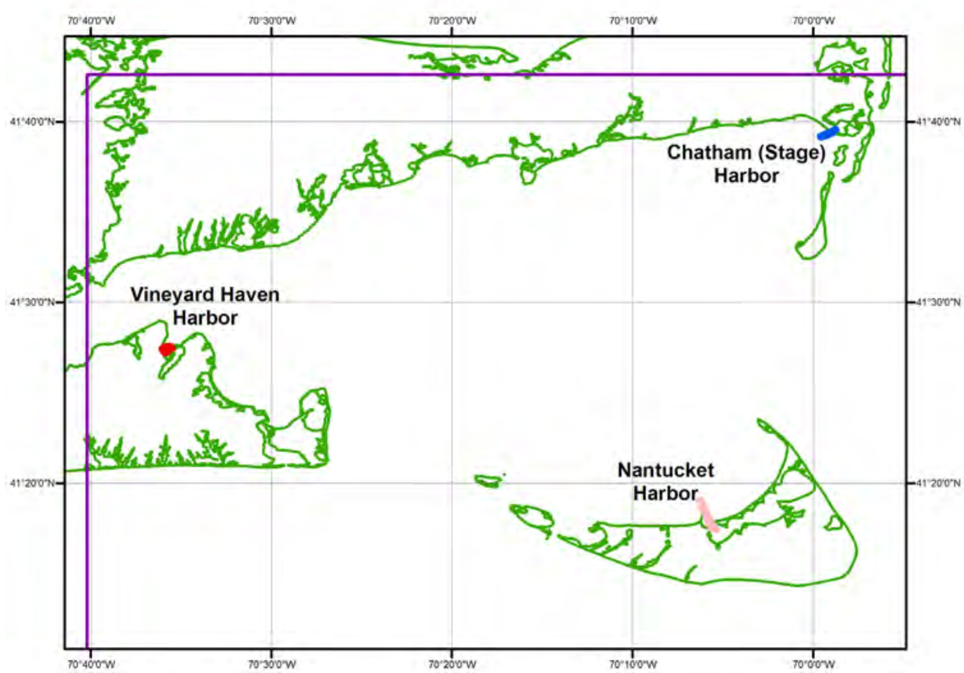

Figure 9. *Coverage of USACE hydrographic surveys in the Nantucket region. DEM boundary in purple; combined coastline in green.*

6. A hydrographic survey of the Federal Navigation Project at Chatham (Stage) Harbor, Chatham, Massachusetts was conducted in 2007. Soundings were taken at prescribed intervals to determine the current condition of the channel and turning basin. Data were collected in the field utilizing Coast Oceanographics Hypack Max v. 4.3a software. Collected information was processed and mapped utilizing Coast Oceanographics Hypack Max 4.3a software, Bentley Microstation V8 and Bentley InRoads SelectCAD v. 8.02. Purpose was to graphically provide bathymetric data for the channel and anchorage. [Extracted from metadata]

7. A hydrographic survey of the Federal Navigation Project at Vineyard Haven Harbor, Martha's Vineyard, MA, was conducted in 2004. Soundings were taken at the prescribed intervals to determine the current condition of channel. Data were collected in the field utilizing Coastal Oceanographics Hypack Max v. 4.3a software. Collected information was processed and mapped utilizing Coastal Oceanographics Hypack Max 4.3a software, Bentley Microstation V8 and Bentley InRoads SelectCAD v. 8.02. Purpose was to graphically provide bathymetric data for the channel and anchorage. [Extracted from metadata]

5) Estimated bathymetry from satellite imagery

The Nantucket region frequently undergoes significant and sometimes rapid coastal morphologic change. On April 17th and 18th, 2007, a breach opened in Norton Point Beach along the south end of Katama Bay, on Martha's Vineyard (Figs. 2, 10 and 11; *Sigelman, 2007*). Opening of the breach altered current and tidal dynamics in the bay and along the southern Atlantic coast, influencing sediment migration, erosion and deposition. Publicly available digital elevation data has not been collected since this morphologic change occurred. Similar recent morphologic change has also occurred around Monomoy Island and in Pleasant Bay on Cape Cod (Figs. 10, 12 and 13). NGDC developed a methodology to convert satellite image ocean color in these areas to estimated bathymetric depths, which is described in Section 3.3.1.

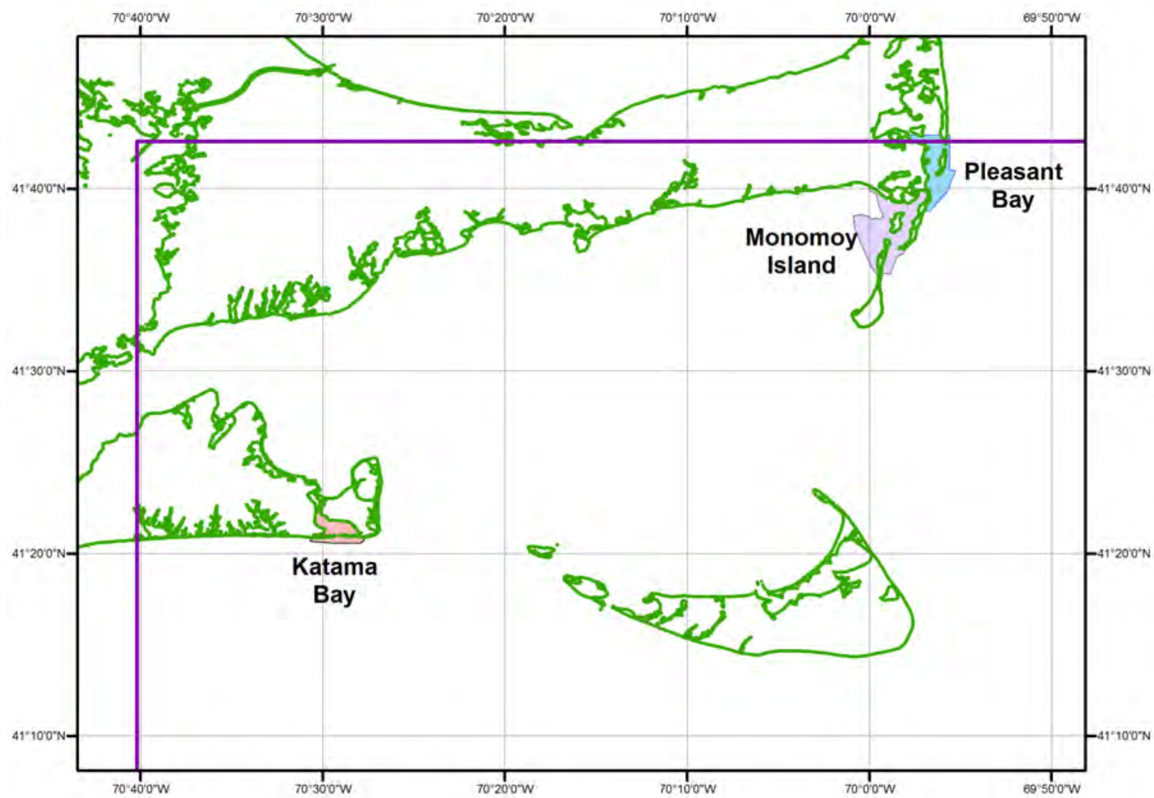

Figure 10. *Coverage of satellite images used to estimate bathymetry in areas of recent, significant morphologic change in the Nantucket region. DEM boundary in purple; combined coastline in green.*

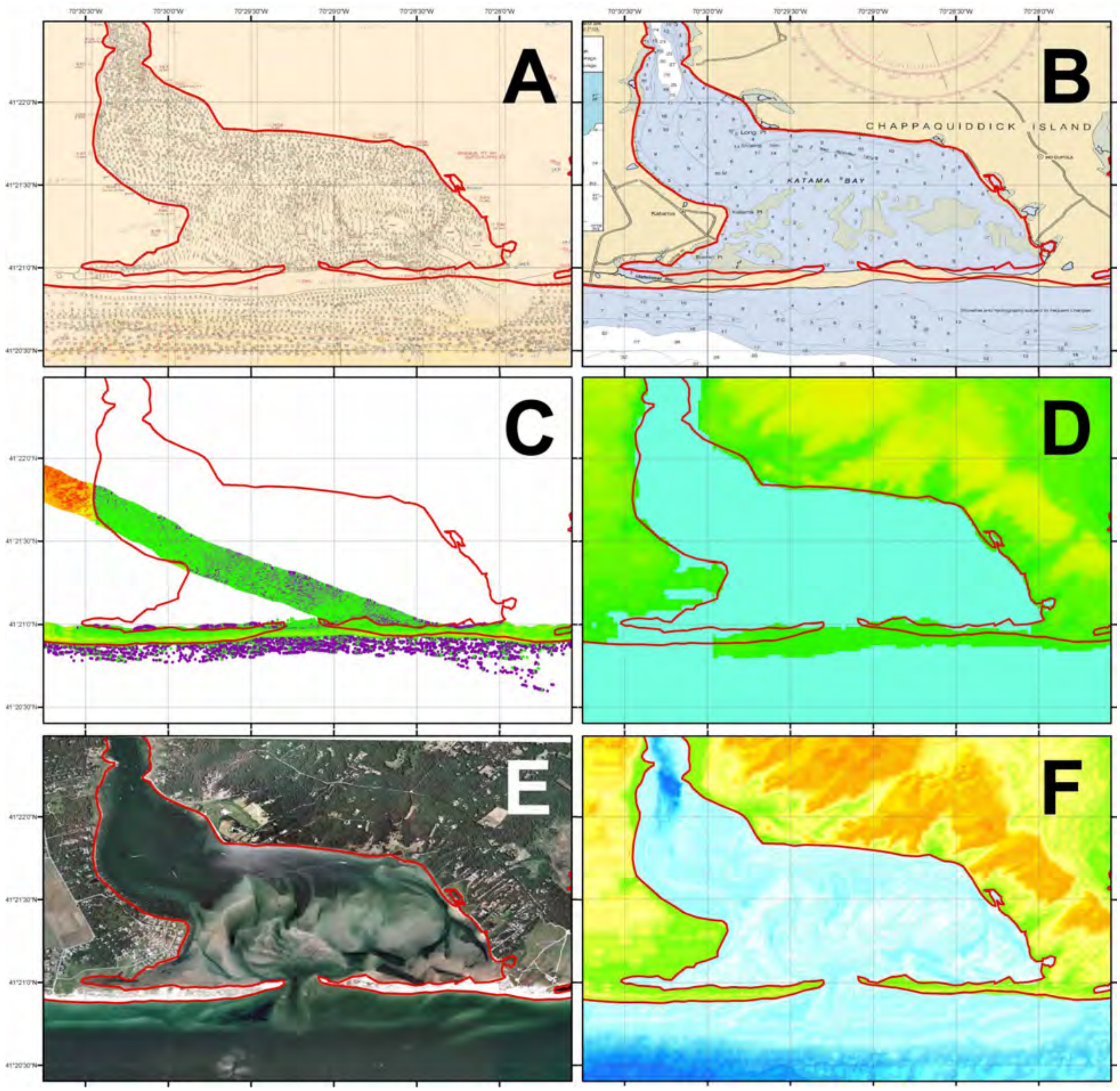

__Figure 11.__ Datasets covering Katama Bay and Norton Point Beach along its south side. A) Smooth sheet of NOS hydrographic survey H08820 conducted in 1964, the only bathymetric survey of the bay. Note that at this time there was an opening at the eastern end of Norton Point Beach. B) NOAA RNC #13238. C) Coastal topographic lidar survey conducted in 2000. D) USGS NED topographic DEM. E) Digital Globe satellite image taken in 2008, following opening of the breach. F) Shaded-relief image of the Nantucket DEM, with Katama Bay, breach and coastal depths derived from the satellite image. Combined coastline in red.

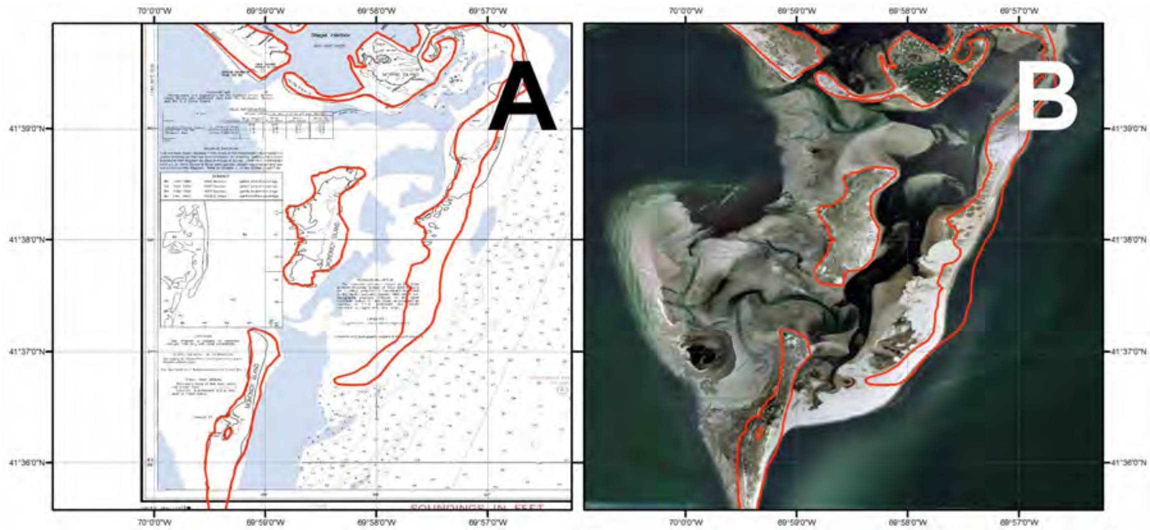

Figure 12. *Morphologic change around Monomoy Island. A) NOAA RNC #13248. B) Digital Globe satellite image taken in 2008. Combined coastline in red.*

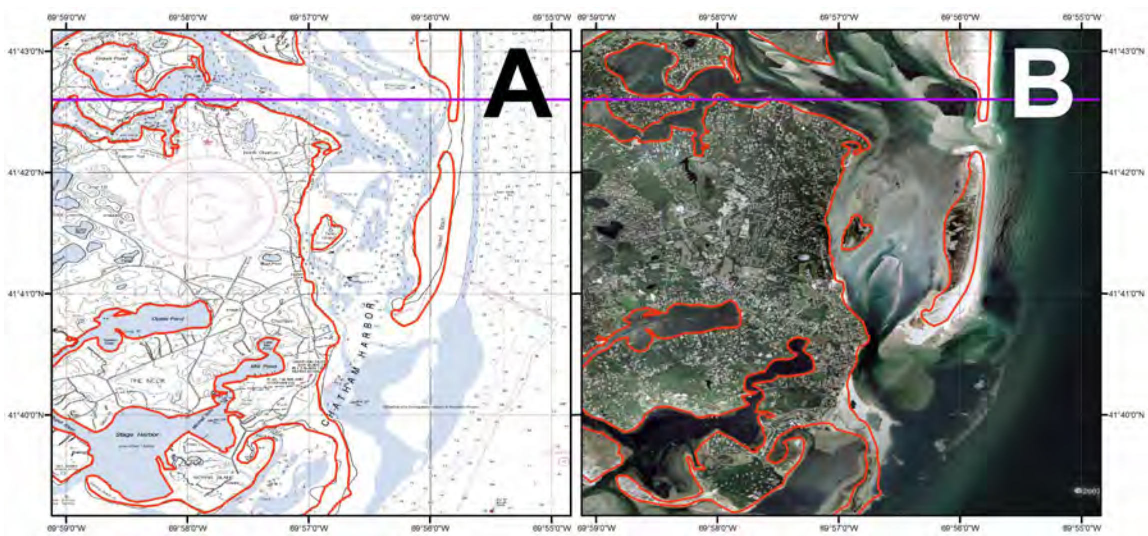

Figure 13. *Morphologic change in Pleasant Bay. A) NOAA RNC #13248. B) Digital Globe satellite image taken in 2008. DEM boundary in purple; combined coastline in red.*

6) NGDC digitized depths

The east jetty at the mouth of Nantucket Harbor has a cut partway out from the coast that is not represented in RNC #13242 (Fig. 14A; *Nantucket Harbor Master, pers. comm.*), nor in the USGS NED DEM (Fig. 14B) or coastal topographic lidar data (Fig. 14C). This cut has scoured an 18-foot-deep depression (*Nantucket Harbor Master, pers. comm.*) that is recognizable in Digital Globe satellite imagery of the harbor (Fig. 14D). NGDC manually digitized soundings in and around the east jetty and scour, using MHW soundings from NOS surveys H08449 and H08479 as a guide (Fig. 14E). The Nantucket DEM roughly captures the east jetty cut and scour as identified in the satellite image (Fig. 14F).

NGDC also manually digitized soundings from the inset in NOS Survey H01948 (shoal at Bishop and Clerks Light) as that part of the survey did not exist in digital form. The NOS survey smooth sheet, in TIFF, was georeferenced in *ArcMap* using the NAD 27 geographic registration lines on the map.

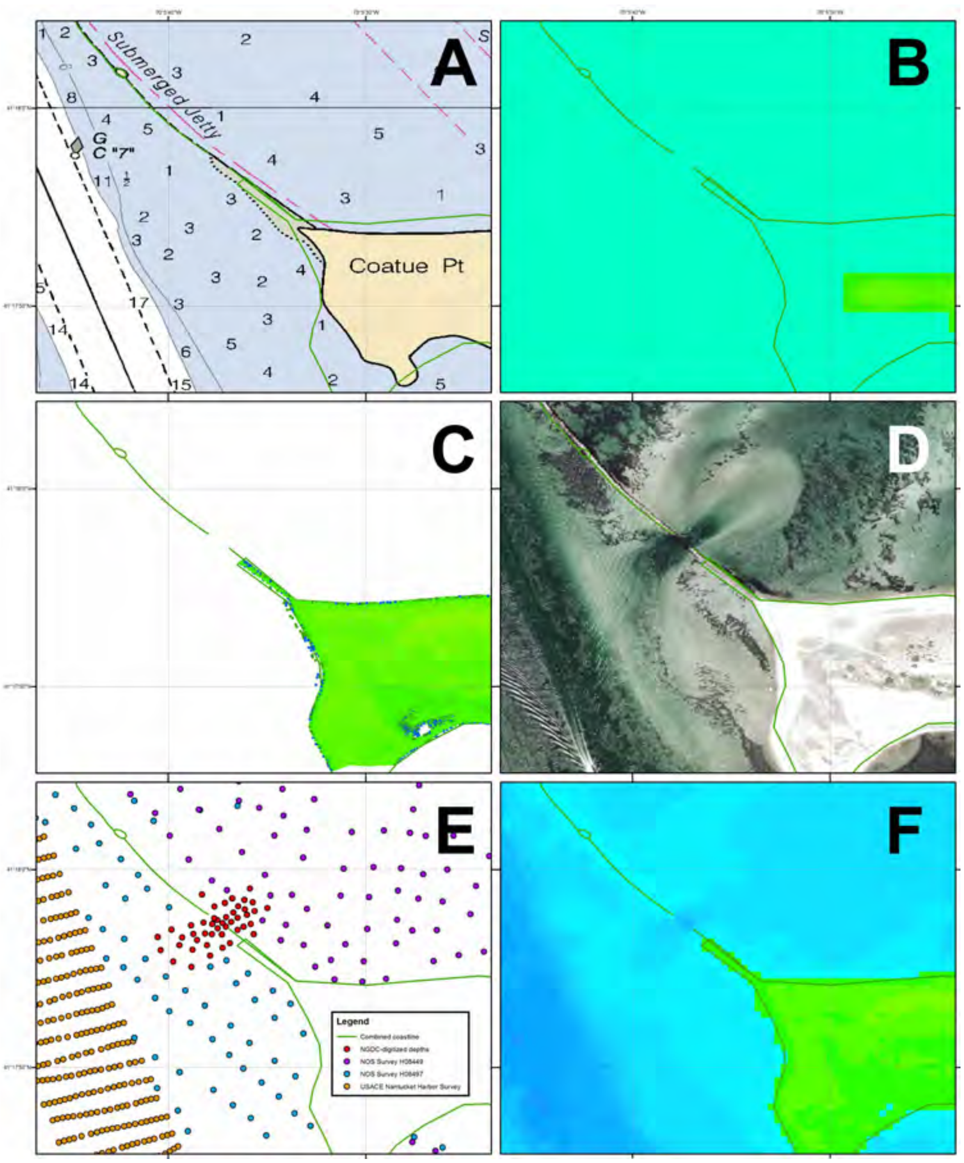

Figure 14. *Datasets covering the cut in Nantucket Harbor's east jetty. A) NOAA RNC #13242. B) USGS NED topographic DEM. C) Coastal topographic lidar survey conducted in 2000. D) Digital Globe satellite image taken in 2008, with scour readily apparent. E) NOS and USACE soundings around the cut in the east jetty, along with NGDC digitized soundings in the cut. F) Color image of the Nantucket DEM, with scour depths derived from the satellite image. Combined coastline in green.*

3.1.3 Topography

Two topographic datasets in the Nantucket region were used to build the Nantucket DEM: one from USGS and one from CSC (Table 8; Fig. 3). NGDC also digitized values along the modified Norton Point Beach, Martha's Vineyard.

Table 8: Topographic datasets used in compiling the Nantucket DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum (meters)*	*URL*
USGS	1999-2006	NED DEM	1/3 arc-second	NAD 83 geographic	NAVD88	http://ned.usgs.gov/
NOAA CSC	1998 and 2000	Coastal topographic lidar	1 to 3 meters	NAD 83 geographic	NAVD88	http://csc.noaa.gov/digitalcoast/
NGDC		Digitized elevation points	~2.5 meters	WGS 84 geographic	MHW	

1) U.S. Geological Survey National Elevation Dataset topography

USGS's National Elevation Dataset (NED) provides complete 1/3 arc-second coverage of the Nantucket region[8]. Data are in NAD 83 geographic coordinates and North American Vertical Datum of 1988 (NAVD88) vertical datum (meters), and are available for download as raster DEMs. The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution (see the USGS Seamless web site for specific source information: http://seamless.usgs.gov). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys, and has been revised using recently collected lidar data. The NED DEMs, downloaded as 5 tiles, contain artificial east-west lineations on Martha's Vineyard and Nantucket Islands and are inconsistent with the Nantucket combined coastline (e.g., Fig. 15). They also contain "zero" elevation values over the open ocean, which were removed from the dataset by clipping to the combined coastline; zero values on "land" were adjusted to a height of 0.1 meters above MHW.

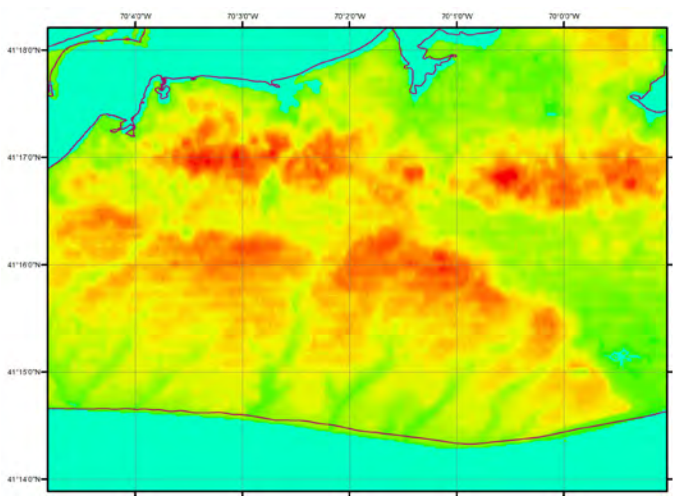

Figure 15. *Color image of USGS NED DEM in the southern part of Nantucket Island. Note east-west lineations, and zero values over water. Combined coastline in dark red.*

8. The USGS National Elevation Dataset (NED; http://ned.usgs.gov/) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Georgia. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc-second), and elevation units (meters). The horizontal datum is NAD 83, except for AK, which is NAD 27. The vertical datum is NAVD88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc-second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED web site]

2) Coastal Services Center lidar topography

CSC provides online access to coastal topographic lidar data from numerous federal agencies through its Digital Coast web site (http://csc.noaa.gov/digitalcoast/). Two joint NOAA/USGS/NASA lidar surveys[9] in the Nantucket region were available through this web site: a winter 1998 survey, and a fall 2000 survey. These data were downloaded from the CSC web site as single files for each survey. Original data were in ASCII XYZ format, and NAD 83 geographic and NAVD88 datums. Due to the large size of the 2000 survey, NGDC separated these data into 16 tiles of 1 million points each for easier visualization and editing. As the two surveys were flown along the coasts of Nantucket and Martha's Vineyard Islands and the eastern coast of Cape Cod, nominally at low tide, they were used to help define the position of the MHW combined coastline in these areas. Both surveys contained returns from the water body surfaces (e.g., Fig. 16), which were manually removed in *ArcMap* by clipping close to the combined coastline.

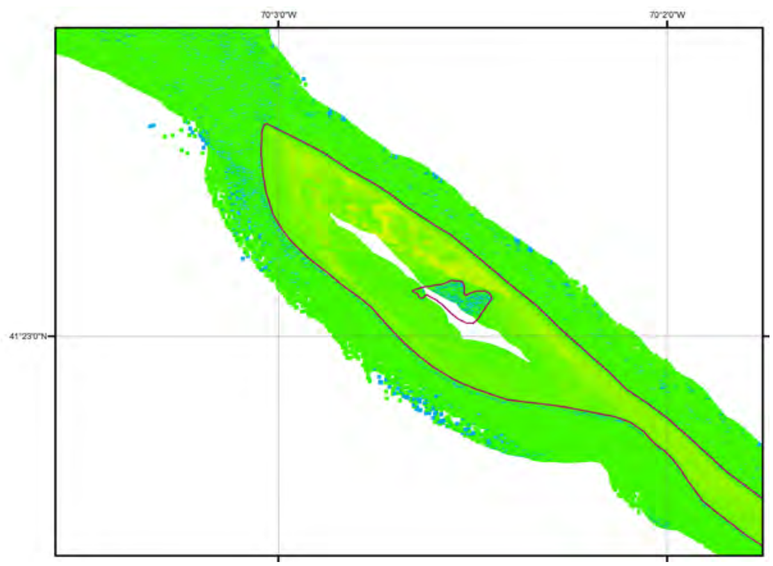

Figure 16. *Coastal lidar survey along the northeastern shore of Nantucket Island. Note returns from the water surface; vertical datum NAVD88. Combined coastline in dark red.*

9. The 1996-2000 NOAA/USGS/NASA Airborne lidar Assessment of Coastal Erosion (ALACE) Project for the US Coastline data set includes data collected from 1996-2000 and covers the states of AL, FL, LA, MS, DE, MD, VA, CT, MA, ME, NH, NJ, NY, RI, NC, SC, GA, CA, OR, WA, TX, OH, and PA. Laser beach mapping uses a pulsed laser ranging system mounted onboard an aircraft to measure ground elevation and coastal topography. The laser emits laser beams at high frequency and is directed downward at the earth's surface through a port opening in the bottom of the aircraft's fuselage. The laser system records the time difference between emission of the laser beam and the reception of the reflected laser signal in the aircraft. The aircraft travels over the beach at approximately 60 meters per second while surveying from the low water line to the landward base of the sand dunes. This data set was collected with a LIDAR (LIght Detection and Ranging) instrument designed and developed by the Observational Sciences Branch (OSB) of NASA at the Wallops Flight Facility in Virginia. The instrument, originally designed for mapping ice sheets in Greenland, is called the Airborne Topographic Mapper or ATM. The ATM II (the latest version), operates with a Spectra Physics laser transmitter, which provides a 7 nanoseconds long, 250 micro joules pulse at a frequency-doubled wavelength of 523 nanometers in the blue-green spectral region. The laser transmitter can function at pulse rates from 2 to 10 kilohertz (kHz). The laser system with a separate cooling unit weighs approximately 45 kilograms (kg) and requires approximately 15 amperes of power at 115 volts. The transmitted laser pulse is reflected to the surface of the earth with the aid of a small folding mirror mounted on the back of a secondary mirror of a rotating scan mirror assembly mounted directly in front of the telescope. The scan mirror, which is rotated at 20 hertz, is comprised of a section of round aluminum stock, machined to a specific off-nadir angle. A scan mirror with the off-nadir angle of 15 degrees was utilized, producing an elliptical scan pattern with a swath width equal to 50 percent of the approximately 700-meter aircraft altitude. The reflected laser pulse is transmitted to a photo-multiplier assembly that consists of a lens, a narrow bandpass filter, and a single photomultiplier tube. Note: The Spatial Reference section of this document may lack fully FGDC-compliant information regarding projection parameters (i.e., Central meridian, false Northing, etc.). The State Plane or UTM zone will be supplied, and the corresponding parameters can be found in Appendix C of: Snyder, John, 1987, Map Projections, a Working Manual (U.S. Geological Survey Professional Paper 1395): Washington, U.S. Government Printing Office. [Extracted from metadata]

3) NGDC digitized elevations

Several features were poorly represented, or not represented at all, in available digital elevation datasets: the newly exposed parts of the Norton Point Beach that jut into Katama Bay at the breach (Figs. 11 and 17), and several coastal jetties and breakwaters. The 2008 Digital Globe satellite image of Katama Bay shows two exposed sand bars jutting into Katama Bay alongside the April 2007 breach (Fig. 17). These sand bars were not present in the 2000 coastal topographic lidar survey, so NGDC generated numerous scattered points on these sand bars, and assigned them an elevation of ½ meter above MHW.

NGDC digitized coastal jetties at Oaks Bluff, Hyannis, Wychmere and Saquatucket Harbors, and the mouths of the Herring and Bass Rivers. Each was assigned an elevation of 1 meter above MHW, with points located every 5 meters along each jetty or breakwater. NGDC also digitized the east and west jetties at the mouth of Nantucket Harbor. Both jetties are submerged at high tide for most of their lengths (*Nantucket Harbor Master, pers. comm.*), so NGDC assigned an elevation of ½ meter below MHW to these jetties, with points every 5 meters along their lengths. The coastal ends of both jetties were measured in the 2000 coastal topographic lidar survey, which was used to ensure their representation in the Nantucket DEM.

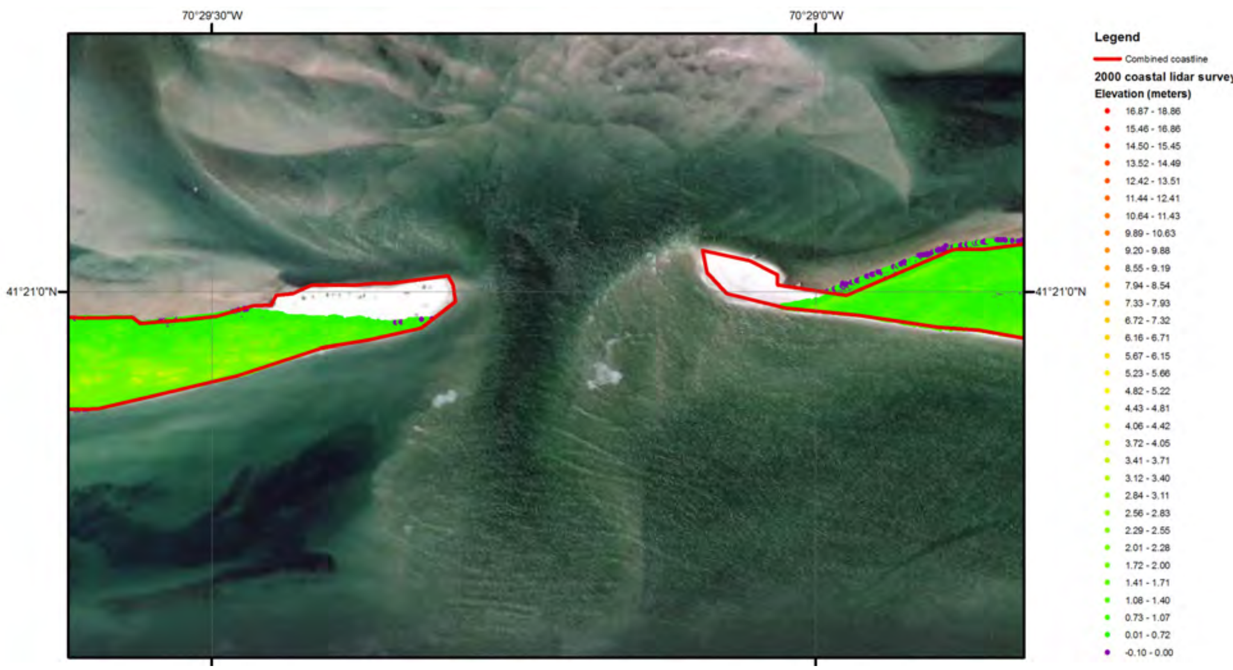

Figure 17. *Satellite image of breach in Norton Point Beach. The breach has moved sand northwards into Katama Bay, building two exposed sand bars that were not present during the 2000 topographic lidar survey.*

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Nantucket DEM were originally referenced to a number of vertical datums including MLLW, MLW, and NAVD88. NOAA maintains eight tide stations in the Nantucket region (Fig. 18). Most of the mainland tide stations have been surveyed to NAVD88, though not the two island stations. All data were transformed to MHW to provide the maximum flooding for inundation modeling. Units were converted from feet to meters as appropriate.

1) **Bathymetric data**

   The NOS hydrographic surveys, the ENC extracted soundings, and the USGS multibeam sonar surveys were transformed from MLLW and MLW to MHW, using the differences as measured at the Nantucket Island NOAA tide station, #8449130 (Table 9; Fig. 18).

2) **Topographic data**

   The USGS NED 1/3 arc-second DEMs and coastal topographic lidar data were originally referenced to NAVD88. Conversion to MHW, using *FME* software, was accomplished by averaging the difference between MHW and NAVD88, as measured at the mainland tide stations (Table 9; Fig. 18).

Table 9. Relationship between MHW and other vertical datums in the Nantucket region.

Vertical datum	*Nantucket Island*	*Conversion value used*
NAVD88	N/A	-0.32
MLW	-0.925	-0.93
MLLW	-0.986	-0.99

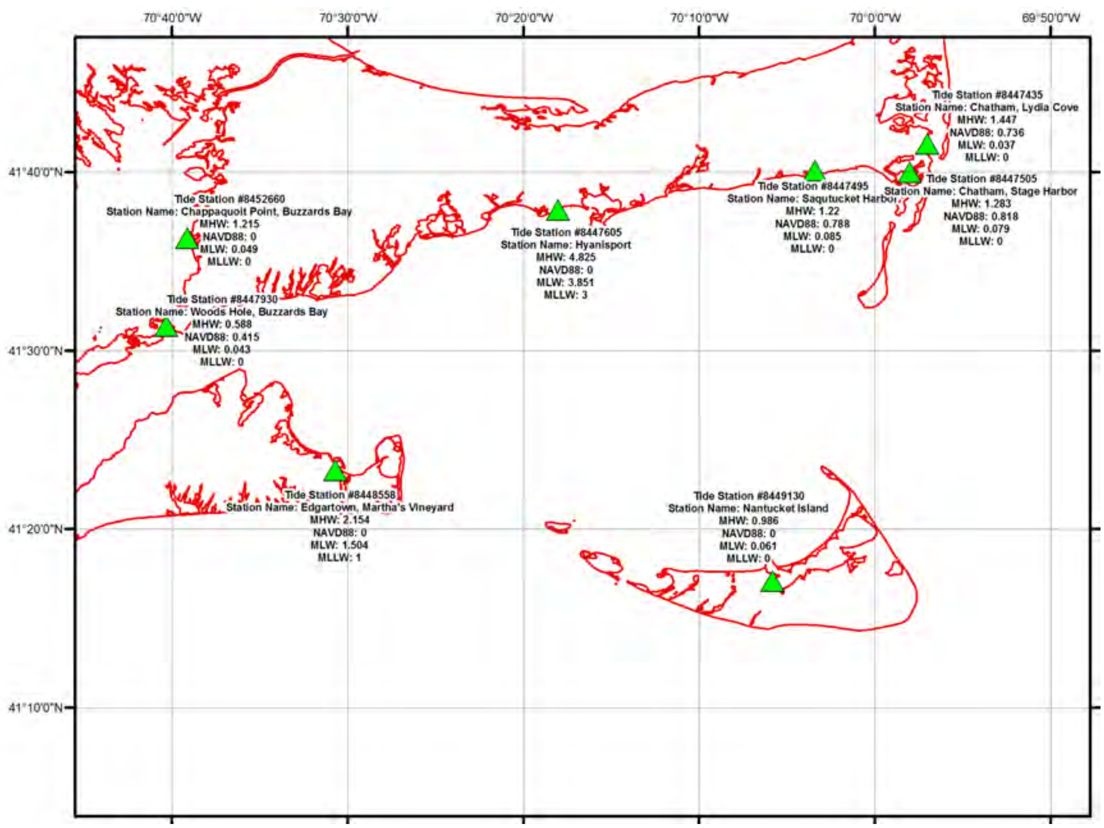

Figure 18. *NOAA tide stations and vertical datum relationships in the Nantucket region.*

3.2.2 Horizontal datum transformations

Datasets used in compiling the Nantucket DEM were originally referenced to WGS 84, NAD 83, and NAD 27 geographic, and NAD 27 and NAD 83 Massachusetts State Plane Mainland (feet) and Island (feet) horizontal datums. The relationships and transformational equations between these horizontal datums are well established. Data in NAD 27 geographic or Massachusetts State Plane were converted to a horizontal datum of NAD 83 geographic using *FME* software.

3.3 Digital Elevation Model Development

3.3.1 Estimating bathymetry from satellite imagery

Ocean depths for the three areas that have undergone recent, significant morphologic change (Katama Bay, Monomoy Island and Pleasant Bay; Fig. 10) were estimated by calculating shallow water depths from satellite images. In each of the areas, Digital Globe satellite images were extracted from *Google Earth Pro*, converted to TIFF and orthorectified in *ArcMap* using stable, identifiable features, such as road intersections and promontories. The images were then converted to 16-bit grayscale (single value per pixel) and compared to older NOS surveys in the area. An approximate logarithmic relationship between pixel value and sounding was calculated for each area using *MatLab* (e.g., Fig. 19), and this equation (Table 10) was applied to the grayscale image for each area to obtain estimated depths. The resulting Arc raster was resampled to 1/3 arc-second, clipped to the combined coastline, and converted to an ESRI point shapefile, which was edited to remove estimated depths from boats, piers, waves and clouds. Depths deeper than -5 meters were set to -5 meters in the Katama Bay area, while depths deeper than -6 meters were set to -6 meters surrounding Monomoy Island and in Pleasant Bay.

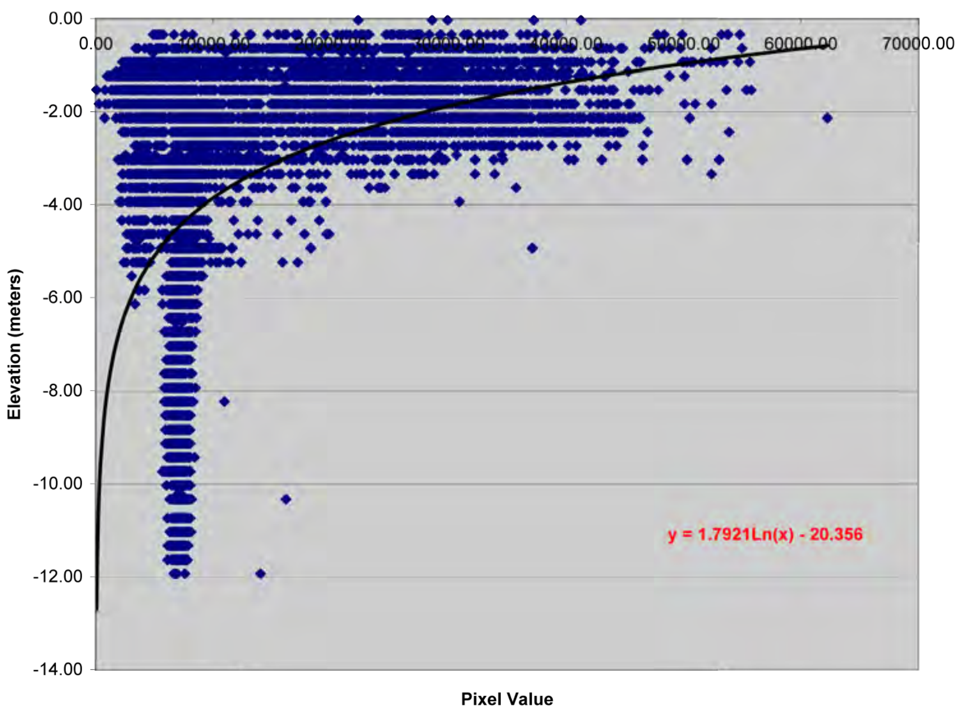

Figure 19. *Graph of pixel value vs. depth surrounding Monomoy Island. Soundings were taken from NOS survey H06472. Note that below about 5 meters depth, the pixel value does not correlate with depth.*

Table 10. Logarithmic equations used to convert satellite images to estimated seafloor depths.

Area	*Equation*
Katama Bay, Martha's Vineyard	y = 1.35 Ln (x-4000) -15
Monomoy Island, Cape Cod	y = 1.8 Ln (x) - 20
Pleasant Bay, Cape Cod	y = 1.8 Ln (x) - 20

3.3.2 *Verifying consistency between datasets*

After horizontal and vertical transformations were applied, the resulting ESRI shapefiles were checked in *ArcMap* for consistency between datasets. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shapefiles were then converted to xyz files in preparation for gridding. Problems included:

- Several areas had undergone significant morphologic change that were not represented in any digital dataset. NGDC used 2008 satellite imagery to estimate bathymetry in these areas.
- Data values over the ocean, bays and rivers in the NED topographic DEMs. The dataset required automated clipping to the combined coastline.
- Many coastal areas in the NED DEMs contained zero values, which were shifted to +0.1 m above MHW.
- Coastal topographic lidar data contained returns from the ocean surface. These data were clipped to the combined coastline.
- Digital, measured bathymetric values from NOS surveys date back over 70 years. The older NOS survey data were excised where more recent bathymetric data exists.
- One NOS survey, H01948, contained an inset detailing the shoal at Bishop and Clerks Light, which did not exist as digital soundings. As no other data were available to depict this feature, NGDC manually digitized inset soundings from this survey to ensure representation of the shoal in the Nantucket DEM.

3.3.3 *Smoothing of bathymetric data*

The NOS hydrographic surveys are generally sparse at the resolution of the 1/3 arc-second Nantucket DEM: in deep water the NOS survey data have point spacing up to 4 km apart. In order to reduce the effect of artifacts in the form of lines of “pimples” in the DEM due to this low resolution dataset, and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing ‘pre-surface’ bathymetric grid was generated using *GMT*, an NSF-funded shareware software application designed to manipulate data for mapping purposes.

The NOS hydrographic point data, in xyz format, were clipped to remove overlap with the USGS and USACE survey data, estimated bathymetry from satellite imagery, NGDC-digitized soundings, and where NOS soundings crossed the modern combined coastline. The NOS data were then combined with these bathymetric data and the ENC sounding data into a single file, along with points extracted from the combined coastline (to provide a buffer along the entire coastline). The coastline elevation value was set at -0.5 m to ensure that the bathymetric surface was below zero in areas where coastal bathymetry data are sparse or nonexistent (e.g., bays).

The point data were median-averaged using the *GMT* tool “blockmedian” to create a 1 arc-second grid 0.05 degrees (~5%) larger than the Nantucket DEM gridding region. The *GMT* tool “surface” was then used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created by “surface” was converted into an ESRI Arc ASCII grid file, and clipped to the combined coastline (to eliminate data interpolation into land areas). The resulting surface was compared with original soundings to ensure grid accuracy (e.g., Fig. 20), converted to a shapefile, and then exported as an xyz file for use in the final gridding process (see Table 11).

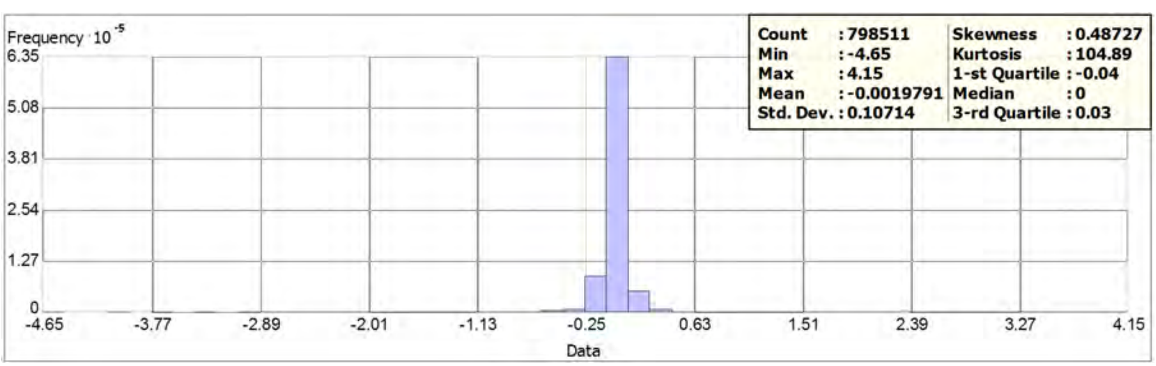

Figure 20. *Histogram of the differences between NOS hydrographic survey H11346 and the 1 arc-second pre-surfaced bathymetric grid.*

3.3.4 Gridding the data with MB-System

MB-System was used to create the 1/3 arc-second Nantucket DEM. *MB-System* is an NSF-funded shareware software application specifically designed to manipulate submarine multibeam sonar data, although it can utilize a wide variety of data types, including generic xyz data. The *MB-System* tool "mbgrid" was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the "mbgrid" gridding algorithm, as relative gridding weights, is listed in Table 11. Greatest weight was given to the USACE hydrographic harbor surveys and coastal topographic lidar data. Least weight was given to the pre-surfaced 1 arc-second bathymetric grid and ENC soundings. Gridding was performed in quadrants with the resulting Arc ASCII grids seamlessly merged in *ArcCatalog* to create the final 1/3 arc-second Nantucket DEM.

Table 11. Data hierarchy used to assign gridding weight in *MB-System*.

Dataset	*Relative Gridding Weight*
Coastal topographic lidar	10 to 100
USGS NED topographic DEM	1
Digitized Norton Point Beach topography	10
USACE hydrographic surveys	100
USGS multibeam swath sonar surveys	10
NOS hydrographic survey soundings	1
Bathymetry derived from satellite imagery	10
ENC soundings	0.1
Nantucket Harbor jetties	10
Pre-surfaced bathymetric grid	0.1

3.4 Quality Assessment of the DEM

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Nantucket DEM is dependent upon the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of about 10 meters: coastal topographic lidar data have an accuracy of approximately 6 meters; NED topography is accurate to within about 10 meters. Bathymetric features are resolved only to within a few hundred meters in deep-water areas. Shallow, near-coastal regions, rivers, and harbor surveys have an accuracy approaching that of sub aerial topographic features. Positional accuracy is limited by: the sparseness of deep-water soundings; potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys; and by the morphologic change that occurs in this dynamic region.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Nantucket DEM is also highly dependent upon the source datasets contributing to DEM cell values. Topographic areas have an estimated vertical accuracy between 0.1 to 0.3 meters for coastal topographic lidar data, and up to 7 meters for NED topography. Bathymetric areas have an estimated accuracy of between 0.1 meters and 5% of water depth. Those values were derived from the wide range of input data sounding measurements from the early 20th century to recent, GPS-navigated sonar surveys. Gridding interpolation to determine values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Slope maps and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Nantucket DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 21). The DEM was transformed to UTM zone 19 coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the UTM-transformed DEM was accomplished using ESRI *ArcScene* (e.g., Fig. 22). Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1/3 arc-second Nantucket DEM in its final version.

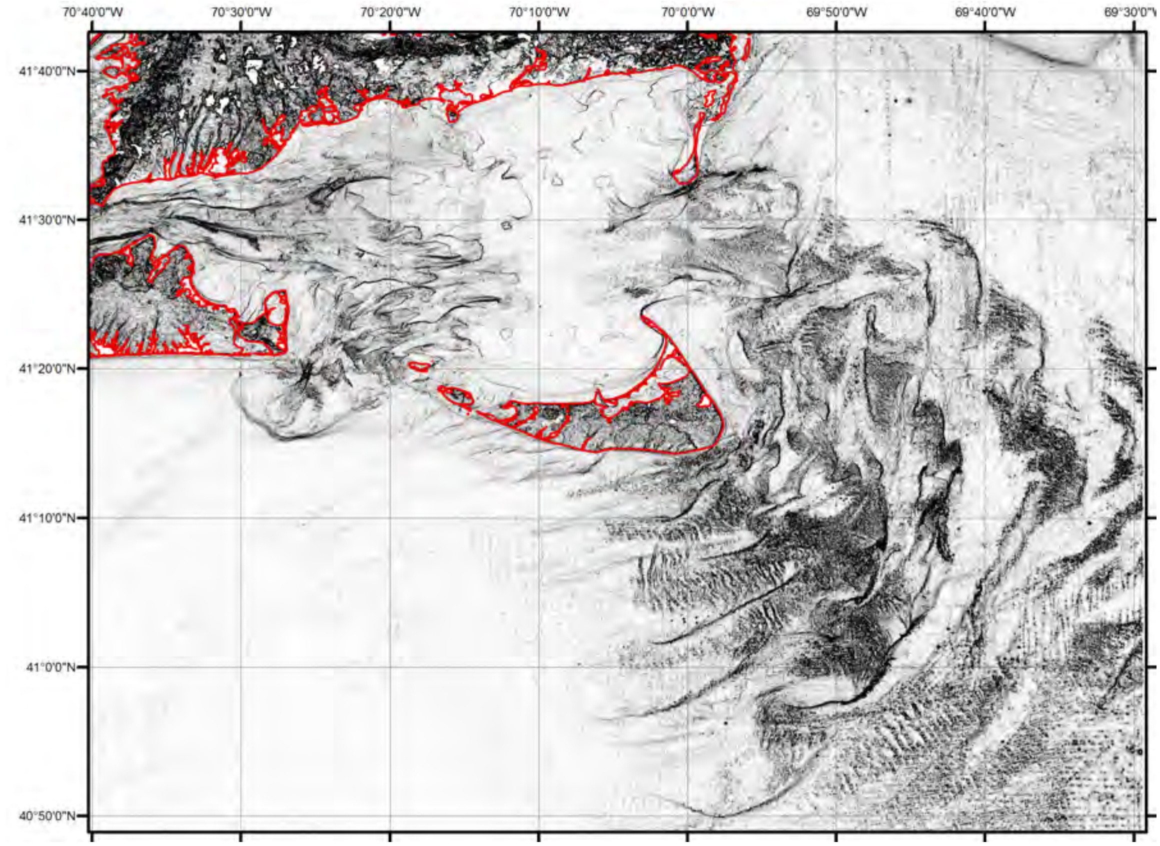

Figure 21. *Slope map of the Nantucket DEM. Flat-lying slopes are white; dark shading denotes steep slopes; combined coastline in red.*

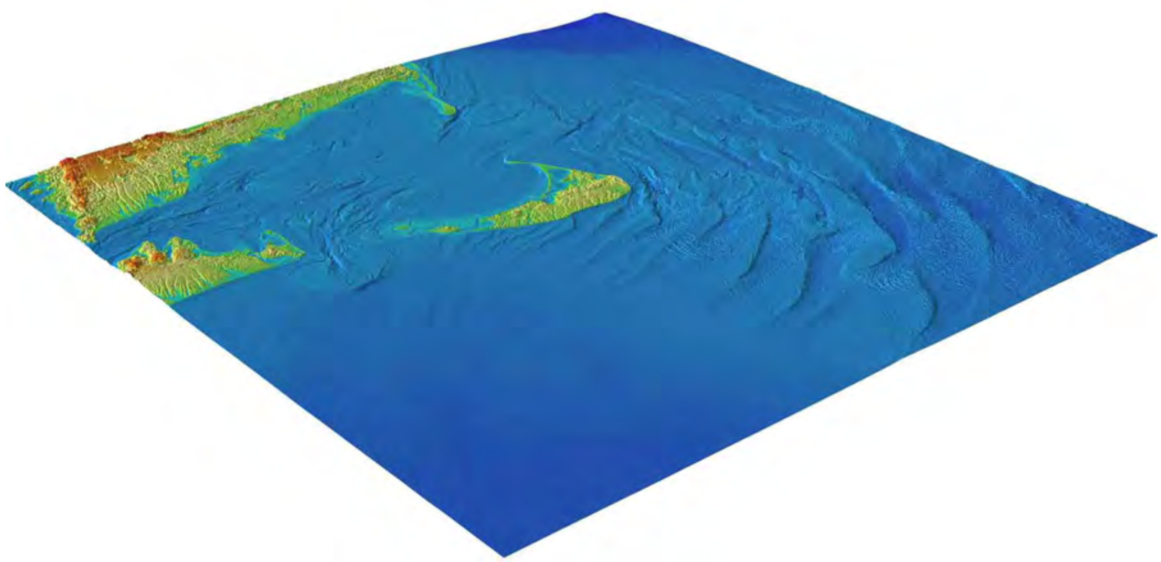

Figure 22. *Perspective view from the southwest of the Nantucket DEM. Vertical exaggeration–times 7.*

3.4.4 *Comparison with source data files*

To ensure grid accuracy, the Nantucket DEM was compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas (i.e., had the greatest weight and did not significantly overlap other data files with comparable weight). A histogram of the differences between a coastal topographic lidar survey file and the Nantucket DEM is shown in Figure 23. Differences cluster around zero, with only a handful of points, in regions of steep topography, exceeding a 1-meter discrepancy from the DEM. Figures 24 to 26 show histograms of other datasets compared to the Nantucket DEM.

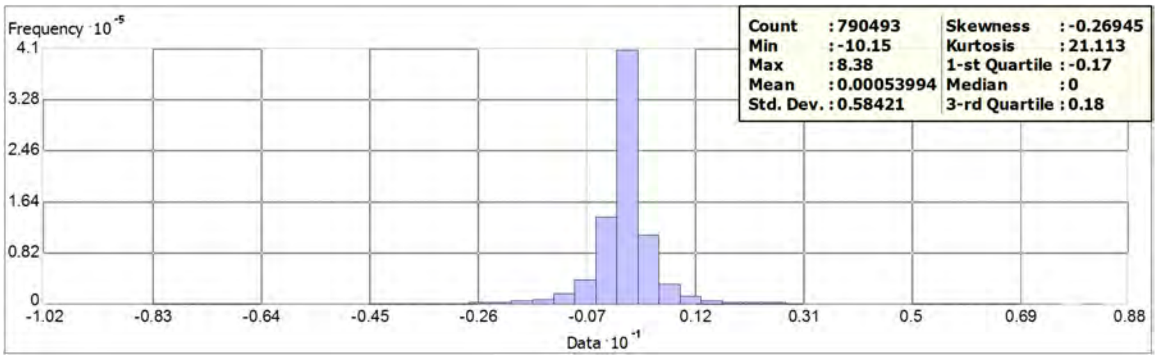

Figure 23. *Histogram of the differences between the 2000 topographic lidar survey along the northern coast of Nantucket Island and the Nantucket DEM.*

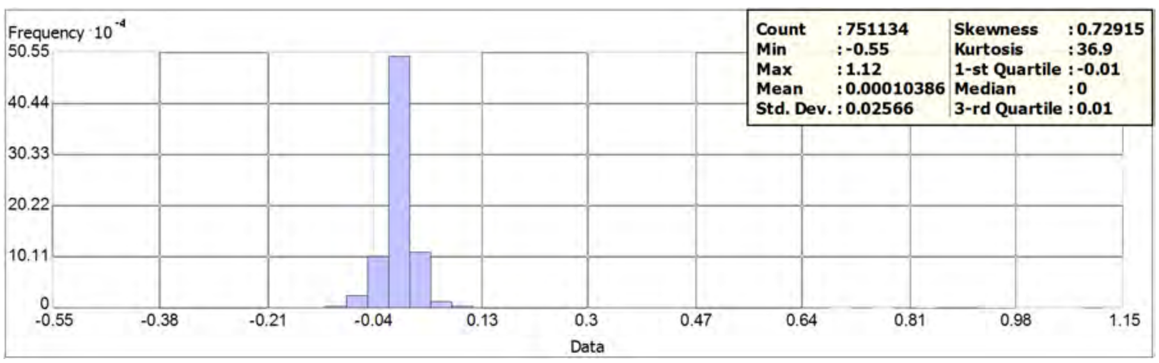

Figure 24. *Histogram of the differences between USGS Cape Cod multibeam swath sonar survey and the Nantucket DEM.*

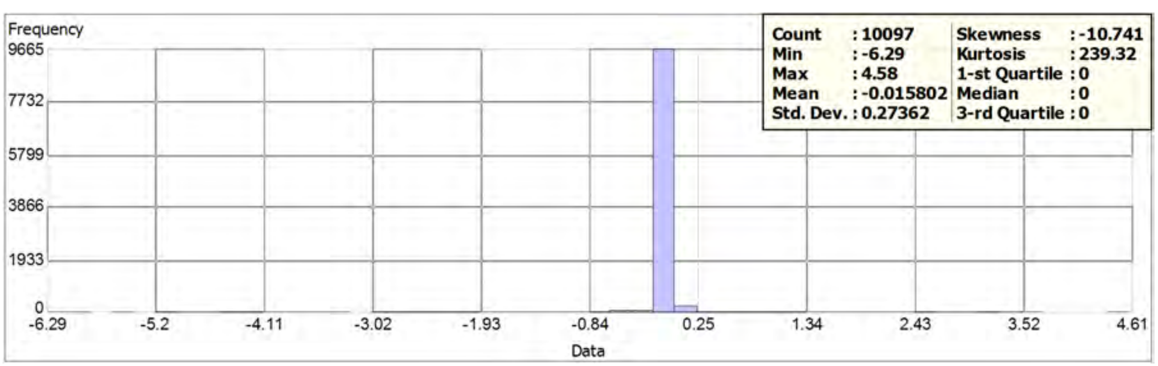

Figure 25. *Histogram of the differences between NOS hydrographic survey H11078 and the Nantucket DEM.*

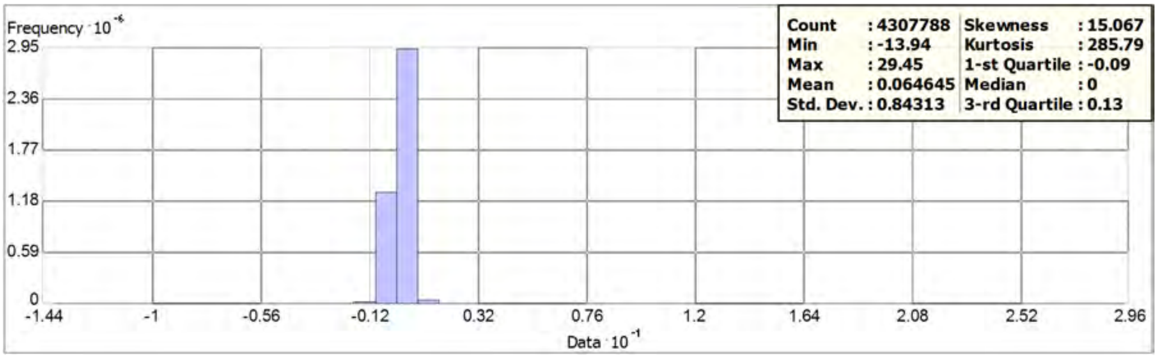

Figure 26. *Histogram of the differences between the USGS NED on mainland Massachusetts and the northwestern part of the Nantucket DEM.*

3.4.5 Comparison with National Geodetic Survey geodetic monuments

The elevations of 388 NOAA National Geodetic Survey (NGS) geodetic monuments were extracted from online shapefiles of monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD 83 (typically sub-mm accuracy) and elevations in NAVD88 (in meters). Elevations were shifted to MHW vertical datum (see Table 9) for comparison with the Nantucket DEM (see Fig. 28 for monument locations). Differences between the Nantucket DEM and the NGS geodetic monument elevations range from -21 to 11 meters, with the majority of them being within a few meters; negative values indicate that the DEM is less than the monument elevation (Fig. 27). Inspection of datasheets for those monuments with significant discrepancy from the DEM show that they are caused by poor accuracy in monument location (+/- 6 arc-seconds; ~180 meters), monuments located on manmade structures such as bridges, piers or lighthouses (not the ground surface), or by monuments that are lost.

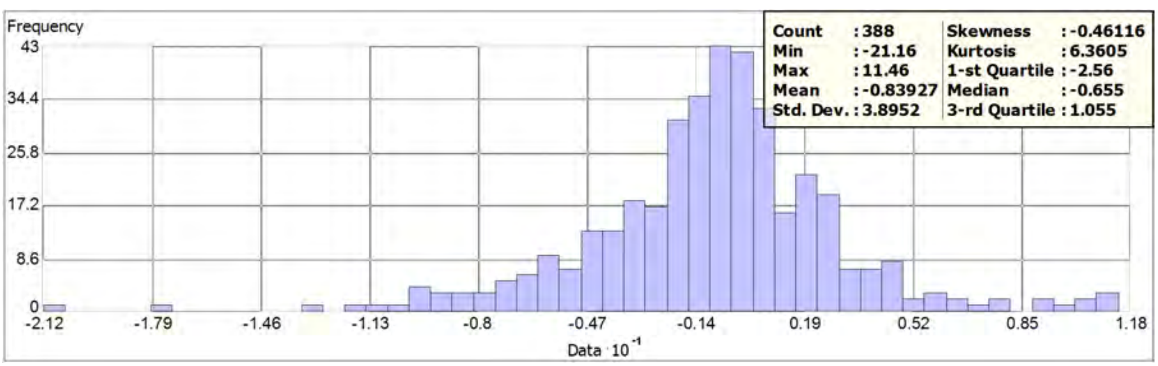

Figure 27. *Histogram of the differences between NGS geodetic monument elevations and the Nantucket DEM.*

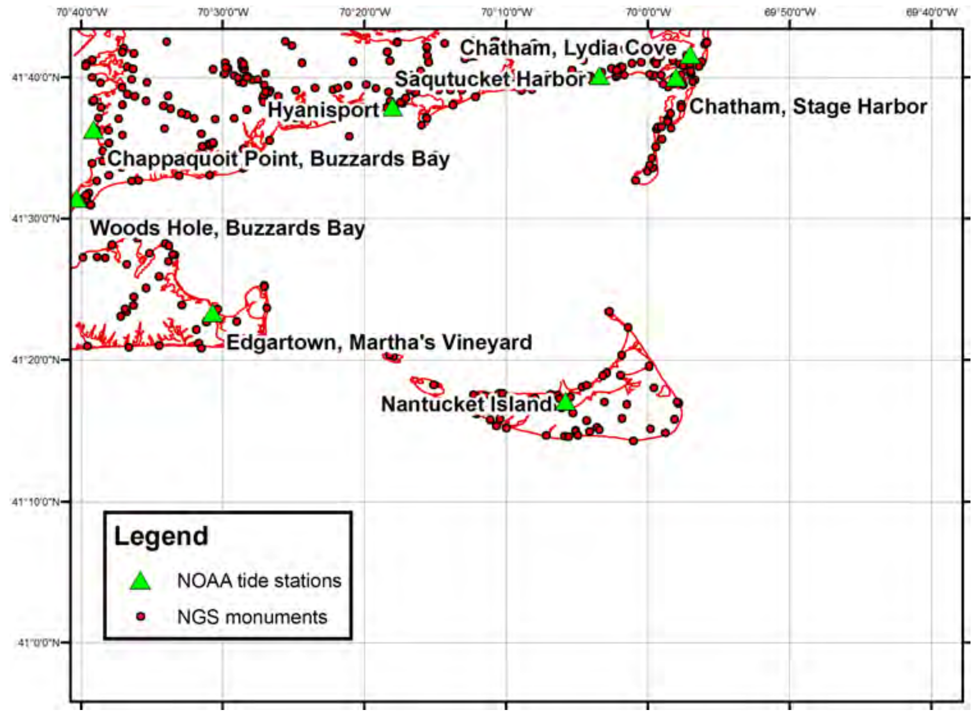

Figure 28. *Location of NGS geodetic monuments and NOAA tide stations in the Nantucket region. NGS monument elevations were used to evaluate the DEM.*

4. Summary and Conclusions

An integrated bathymetric–topographic DEM of the Nantucket, Massachusetts region, with cell size of 1/3 arc-second, was developed for the PMEL NOAA Center for Tsunami Research. The best available digital data from U.S. federal and state agencies were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using *ArcGIS*, *FME*, *GMT*, *MB-System* and *Quick Terrain Modeler* software.

Recommendations to improve the Nantucket DEM, based on NGDC's research and analysis, are listed below:

- Conduct hydrographic surveys in near-shore areas, especially in harbors, bays and estuaries, and where recent, significant morphologic change has occurred (i.e., Katama Bay, surrounding Monomoy Island, and Pleasant Bay).
- Complete topographic lidar surveying of coastal areas in entire region.

5. Acknowledgments

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Nautical Chart #13237 (ENC), 3rd Edition, 2007. Nantucket Sound and Approaches. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #13238 (RNC), 3rd Edition, 2007. Martha's Vineyard Eastern Part. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #13242 (ENC), 3rd Edition, 2001. Nantucket Harbor. Scale 1: 10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

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Sigelman, N., 2007. Storm breaches Norton Point Beach. The Martha's Vineyard Times, April 19, 2007. http://www.mvtimes.com/news/2007/04/19/norton_point_beach.php

7. Data Processing Software

ArcGIS v. 9.2, developed and licensed by ESRI, Redlands, Massachusetts, http://www.esri.com/

FME 2008 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/

GEODAS v. 5 – Geophysical Data System, shareware developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/

GMT v. 4.3.0 – Generic Mapping Tools, shareware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/

MB-System v. 5.1.0, shareware developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/

Quick Terrain Modeler v. 6.0.1, lidar processing software developed by John Hopkins University's Applied Physics Laboratory and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/